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Project Cost Estimate

Wabamun Area CO_2 Sequestration Project (WASP)

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INTRODUCTION

This chapter evaluates the cost of sequestering CO_2 into the porous brine-filled Nisku formation in the Wabamun Lake area.

Deep aquifers have been identified as having the potential to store very large volumes of CO_2. However, the typical benchmark rate for CO_2 injection is only 1 Mt/year when studying storage performance. This rate is very low when considering the scale needed by storage technology to play a significant role in managing global emissions. As a result, the reservoir modelling effort for the WASP project addressed the feasibility of injecting large volumes of CO_2 into the Nisku aquifer, which is a deep aquifer located in the Wabamun Lake area. Because of injection limitations in the aquifer, several injection scenarios were modelled to improve the volume of CO_2injected. The scenarios include vertical or horizontal injection wells as follows:

- Scenario 1—vertical injection wells only.
- Scenario 2—vertical wells with hydraulically fractured stimulation.
- Scenario 3—horizontal injection wells only.
- Scenario 4—horizontal wells with hydraulic fracture stimulation.

The total injection cost for all four scenarios is addressed in this section.

The objective of this report is to estimate the cost per ton for sequestering CO_2 for large sequestration projects, such as the Wabamun Area CO_2 Storage Project. The cost estimate takes into account all of the costs incurred from the wellhead down into the formation and includes the cost of a CO_2 monitoring program. The cost for capturing, transporting and pressurizing CO_2 to get it to the injection site are outside the scope of these analyses. An injection period of 50 years and a total volume of CO_2 ranging from 0.21 to 0.43 GTons (GT) were assumed for the four different reservoir analyses.

1. PROJECT COSTING METHODOLOGY AND SOURCES

1.1 Fifty Years of Injection

In the reservoir model, a practical estimate for the storage capacity was determined using the maximum amount of CO_2 that can be injected in a given period of time (50 years) in a localized injection area (~ 30 km × 90 km) without exceeding the breakdown pressures for the formation (see Reservoir Model section for further details). Based on four different types of injection wells, the total CO_2 that could be stored ranged from 0.21 to 0.43 GT (Table 1). The lowest volume of injected CO_2 was from vertical injection wells without stimulation (Scenario 1) and the largest volume from hydraulically fractured stimulated horizontal wells (Scenario 4). The reservoir injection model also showed that injecting CO_2 using fracture stimulated vertical wells (Scenario 2) provided a higher total of stored volume than horizontal wells without stimulation (Scenario 3).

Table 1: Total injected volume of CO_2 and plume size for each 50-year scenario.

Scenario		CO_2 (GTons)	CO_2 Plume Radius (km)	CO_2 Plume Area (km)
1	Vertical Injection Wells	0.21	5	785
2	Vertical Injection Wells with Fracture Stimulation	0.34	11	1,272
3	Horizontal Injection Wells	0.31	11	1,159
4	Horizontal Injection Wells with Fracture Stimulation	0.43	13	1,608

1.2 Cost Model Development

The objective of the cost model is to estimate the total cost for CO_2 sequestration, which has been defined as the cost for operating CO_2 injection from the wellhead into the formation. The model includes the costs associated with evaluating and preparing the site for injection, as well as all capital expenditures and operating costs for conducting injection for a period of 50 years. Project costs also include CO_2 monitoring during the injection phase and the two phases of post-injection. During the first 10 years a rigorous verification monitoring program is likely, followed by 90 years of monitoring to fulfill anticipated regulatory requirements. The model does not include the costs for pipelining CO_2 to the wellhead or any related acquisition or pressurization costs. Costs have been estimated using a variety of sources, and reflect as accurately as possible current 2009 dollars. Uncertainty in the estimates is addressed by adding a high and low estimate for each actual cost item based on a judgment of the uncertainty of the values. Monte Carlo simulations are used to obtain probability distributions for the cost per ton of CO_2 sequestered.

The cost items in the model are grouped into

- site planning and preparation;
- injection well costs;
- well injection operating costs;
- well abandonment costs;
- surface monitoring well costs;
- 4D seismic costs;
- monitoring operating expenditure;
- surface monitoring; and
- other cost, such as surface lease, project management, administration, and engineering services, and equipment replacement.

Below are the details of the individual cost groups broken into individual cost items.

1.2.1 Site Planning and Preparation

The site planning and preparation cost estimate is shown in Table 2. Geological site characterization includes the work needed to identify, secure and plan an injection site and to complete the data gathering and analyses required to prepare the permit application. The analyses include geological, geophysical, geochemical, geomechanical, reservoir injection well design, and the monitoring program. Hourly employee rates are from the Canadian National Occupational Classification (NOC) database, and time estimates are based on the experience of the individuals conducting the WASP project. Other estimates are based on expert judgment within team member expert area(s) or by soliciting advice from other experts. The total cost for conducting site planning and preparation is ~ $1.6 million CAD. Typical research-related tasks that are included in pilot studies have not been included in this cost estimate, since the purpose of the exercise is to come up with a realistic cost estimate for a commercial project.

Table 2: Cost estimates for site planning and preparation.

Categories	High (CAD)	Actual (CAD)	Low (CAD)	Source
Geological site characterization	260,700	208,560	156,420	1 year FTE * 1920 h/year * 2.5 fully loaded FTE cost * hourly rate NOC code 2113 @ $43.45.
Conventional core laboratory work	6,667	5,000	3,333	Assume 3 samples per active well, 10 wells, cost for sample $100–200 USD per EPA (2008). USD/CAD = .9.
Geochemical analysis	130,350	104,280	78,210	0.5 year FTE * 1920 h/year * 2.5 fully loaded FTE cost * hourly rate NOC code 2113 @ $43.45 + laboratory samples.
Geochemical laboratory costs	601,020	601,020	601,020	6 samples per active well, 1 well per township, cost for sample $1350 CAD + 40% overhead.
Geophysics	260,700	208,560	156,420	1 year FTE * 1920 h/year * 2.5 fully loaded FTE cost * hourly rate NOC code 2113 @ $43.45.
2D seismic line	20,000	–	–	Estimate.
Geomechanical analysis of leakage risk	130,350	104,280	78,210	0.5 year FTE * 1920 h/year * 2.5 fully loaded FTE cost * hourly rate NOC code 2145 @\ $43.45 (USD per hour 96.4 SPE).
Geomechanical laboratory costs	37,500	30,000	27,000	5 different horizons cost per test set (5 tests) $6000 CAD.
Reservoir engineering and injection design	260,700	208,560	156,420	1 year FTE * 1920 h/year * 2.5 fully loaded FTE cost * hourly rate NOC code 2145 @ $43.45.
Leakage risk of existing wells	54,313	43,450	32,588	100 wells * 4 h * 2.5 fully loaded FTE cost * hourly rate NOC code 2145 @ $43.45.
Risk analysis	65,175	52,140	39,105	3/12 FTE *1920 h/year * 2.5 fully loaded FTE cost * hourly rate NOC code 2145 @ $43.45.
Total Cost	**1,827,474**	**1,565,850**	**1,328,726**	

1.2.2 Injection Well Costs

A total of 10 injector wells were included in the cost model. The well costs for the vertical injection wells in Scenario 1 were based on the detailed cost estimate for drilling and completing a vertical injection well as described in the Well Integrity section of this report. Vertical wells with a total length of 1960 m and production packing set at 1890 m was used for the base case. Since the Nisku formation dips down towards the west and the reservoir top depth varies between 1680 m and 2480 m, the depth of the 10 injection wells were evenly distributed to account for these factors. The lowest cost for an injection well within the Nisku formation top is at 1680 m and is shown in Table 3 (middle column).

For injection Scenario 2, vertical wells using hydraulic fracturing stimulation included a one-stage fracture estimated at a cost of $50,000 CAD for each well. For the two scenarios involving horizontal wells, the initial cost model was modified to include a 2500 m-long horizontal injection section within the Nisku formation. Well depths for the two horizontal injection scenarios were evenly distributed for the 10 injection wells. For Scenarios 3 and 4, the difference is an estimated $360,000 CAD for four hydraulic fracturing stimulations, which has been included in Scenario 4. The cost of the most expensive well from Scenario 4 with hydraulic fracturing stimulation and a Nisku formation top depth of 2480 m is ~ $3.5 million CAD (see Table 3, last column). The annual cost for the daily operation of the wells is estimated to be $83,000 CAD plus $1 CAD per metre of well depth.

Table 3: Cost estimates for drilling and completion of injection wells.

Injection Well Cost	Cost of Vertical Well (no stimulation)	Cost of Horizontal Well (with stimulation)
Drilling Cost		
Well fixed costs	168,920	168,920
Fixed depth-based well costs	154,463	346,361
Variable depth-based well costs	219,772	317,415
Time-based drilling cost per day	297,849	1,496,259
Fixed drilling cost	33,000	89,000
Completion Cost		
Completion fixed costs	38,000	73,513
Depth based completion costs	74,545	22,402
Time-based completion costs	138,840	208,260
Five-day injection test	65,000	114,275
Stimulation fracture	0	360,000
Total well cost	**1,190,389**	**3,196,405**
Total well cost plus 5% contingency	**1,249,909**	**3,356,225**

1.2.3 Well Abandonment Costs

The well integrity study identified 15 wells in the overall study area that needed to be abandoned or re-abandoned. Three of the wells are suspended, but have not been properly abandoned. The cost to abandon these wells is taken from PSAC (2008) and is shown in Table 4. The 12 wells identified in the well integrity analysis are in need of a workover with the well re-entered and new cement plugs installed in the Nisku reservoir interval. The existing plugs will be drilled out and new cement plugs installed for a proper abandonment. Table 4 gives the cost for re-entering, plugging and abandoning these 12 wells. The cost is based on the injection well cost model and added abandonment cost from PSAC (2008). The wells should be abandoned before the area is pressurized, since the integrity of the existing casing is unknown and may not have the integrity for holding elevated pressures (see Well Integrity section). To avoid the pressure plume that would be encountered when entering these wells, it is assumed that two wells will be abandoned each year in the first years of the project.

Table 4: Cost estimate for plugging and abandonment.

Year Abandoned	High Monitoring Well Cost	Actual Monitoring Well Cost	Low Well Cost	Monitoring Well Type
2010	31,500	21,000	15,750	suspended
2010	437,422	218,711	109,355	old
2011	31,500	21,000	15,750	suspended
2011	437,422	218,711	109,355	old
2012	31,500	21,000	15,750	suspended
2012	437,422	218,711	109,355	old
2013	437,422	218,711	109,355	old
2013	437,422	218,711	109,355	old
2014	437,422	218,711	109,355	old
2014	437,422	218,711	109,355	old
2015	437,422	218,711	109,355	old
2015	437,422	218,711	109,355	old
2016	437,422	218,711	109,355	old
2016	437,422	218,711	109,355	old
2017	437,422	218,711	109,355	old
Total Cost	**5,343,559**	**2,687,530**	**1,359,515**	

1.2.4 Monitoring

The monitoring program is a combination of four functions: installing a limited set of monitoring wells with access to the injection horizon, conducting surface monitoring, detecting surface CO_2 leakage and CO_2 movement in the subsurface, and performing 4D seismic monitoring. In the cost model, it is assumed that there will be the same number of injection and monitoring wells, and half of the monitoring wells will be existing wells that have been converted. The cost to drill and complete new wells or convert existing wells is shown in Table 5 and were obtained by modifying the well injection cost model. The cost for the monitoring equipment for surface fluid sampling and downhole measurement is given in Table 6. Downhole equipment for measuring temperature and pressure, as well as downhole CO_2 gauges (when available), is included. Micro-seismic phones will be installed downhole to locate CO_2 movement in the subsurface caused by the injection process. A VSP run is included for improving the 4D seismic resolution. The annual operating cost for the monitoring wells is shown in Table 7.

The objective of the surface monitoring program is to detect CO_2 leakage and CO_2 movement in the subsurface. Direct measurement of CO_2 flux to the surface can be detected using ground-surface accumulation chambers. Chemical and isotope signatures can also be detected, which can determine the source of the CO_2 (Oldenburg and Lewicki, 2003). The disadvantage with discrete measurement is that point leakage can go undetected if there is no measurement near the leakage. Atmospheric detection of CO_2 would be a mitigation that would require continuous field-wide measurement. Any ground water well in the injection area is assumed to be regularly monitored to identify potential leakage into potable water. Surface monitoring can also be used to identify CO_2 plume movement by using surface gravity measurement and satellite data for satellite interferometry and satellite land topography. See Table 8 for a summary of the cost for surface monitoring.

Table 5: Cost for monitoring wells.

Type	Year Installed	Drill and Complete New Monitoring Well (CAD)	Converting Existing Well to Monitoring Well (CAD)	Well Depth (m)	High Monitoring Well Cost (CAD)	Actual Monitoring Well Cost (CAD)	Low Well Cost (CAD)
New	2010	1,059,678	–	1600	1,335,986	1,183,845	1,094,687
Converted	2011	–	678,260	1600	1,187,730	802,426	427,123
New	2012	1,127,815	–	1800	1,410,936	1,251,981	1,159,417
Converted	2013	–	735,734	1800	1,273,941	859,901	455,860
New	2014	1,195,951	–	2000	1,485,886	1,320,118	1,224,147
Converted	2015	–	793,208	2000	1,360,152	917,375	484,597
New	2016	1,264,088	–	2200	1,560,837	1,388,255	1,288,877
Converted	2017	–	850,683	2200	1,446,364	974,849	513,335
New	2018	1,332,225	–	2400	1,635,787	1,456,391	1,353,607
Converted	2019	–	908,157	2400	1,532,575	1,032,324	542,072
Total Cost		**5,979,757**	**3,966,042**		**14,230,195**	**11,187,465**	**8,543,723**

Table 6: Cost for monitoring equipment installed in wells.

Type of measurement	Objective	High (CAD)	Actual (CAD)	LOW (CAD)	Source
VSP	Improve 4D seismic and identify changes in velocity profile near wellbore with time	14,300	13,000	11,700	$1000 m * $13/m for regular well logging (PTAC 2008).
Fluid sampling equipment	To identify changes of composition in formation fluids	37,500	30,000	22,500	Estimate from EPA (2008).
Wireline logging		–	–	–	Cost included in the well design.
Dual pressure and temperature quartz gauges	Changes in pressure and temperature during and after injection	19,040	18,667	18,293	Quote from leading manufacturer.
Down hole CO_2 concentration gauge	Measure change in CO_2 concentration in wellbore fluid	40,000	20,000	10,000	Estimate of sensors currently being developed.
Micro-seismic phones	Measure micro-seismic events	59,500	42,500	25,500	$20,000 per well + $22,500 in surface equipment per well (estimate)
Total Cost		**170,340**	**124,167**	**87,993**	

Table 7: Annual operating cost for monitoring wells.

Type of Measure-ment	Objective	Description	High (CAD)	Actual (CAD)	Low (CAD)	Source
Continuous well monitoring: analytical costs	Fate of CO_2 in target formation	Direct measurement of carbon content in reservoir fluids obtained from five observation wells	17,640	16,800	15,960	Analytical cost per sample $850 plus field work $150/sample = $1000 times # of samples.
Continuous well monitoring	Identify changes of composition in formation fluids	Pressure, temperature, CO_2 and fluid sampling	10,863	8,690	6,518	1/12 FTE *1920 h/year * 2.5 fully loaded FTE cost * hourly rate NOC code 2145 @ $43.45.
Micro-seismic events	Measure the micro-seismic events to identify areas with movement in reservoir and caprock		5,431	4,345	3,259	0.25 months engineer time per year – 2/12 FTE *1920 h/year * 2.5 fully loaded FTE cost * hourly rate NOC code 2145 @ $43.45.
Reporting to authorities			5,431	4,345	3,259	0.25 months FTE *1920 h/year * 2.5 fully loaded FTE cost * hourly rate NOC code 2145 @ $43.45.
Total Cost			**39,365**	**34,180**	**28,995**	

Table 8: Cost for surface monitoring.

Type of measure-ment	Objective	Description	Test Frequ-ency (year)	High (CAD)	Actual (CAD)	Low (CAD)	Source
Surface CO_2 baseline	Leaked CO_2 to surface	Direct measurement of CO_2 concentration in the air and vadose zone above the reservoir. Use ground-surface accumulation chambers.	2	3,551,016	1,775,508	–	$19,000 USD per unit, 1 unit per 1000 measurement, density 100 m × 100 m grid over 25% of 4987 km + Prof. Awuah-Offei pers. comm., 3,4 or 5 measurements per hour, NOC code 2254 @ $19.21.
Surface gravity measurement	Plume movement	Performed over whole study area	2	935,063	748,050	561,038	$150 per km^2 (estimate) over whole WASP area 4987 km^2.
Topographic heave satellite interferometry	Measure topo-graphic heave	Satellite interferometry	2	41,165	39,204	37,244	$4000 USD/0.9 USD CAD per 100 km × 100 km radarsat image 2 times per year * 2/12 FTE *1920 h/year * 2.5 fully loaded FTE cost * hourly rate NOC code 2145 @ $43.45.
Topographic heave	Measure topo-graphic heave	Satellite land topography mapping	2	623,375	498,700	374,025	$100 per km^2 (estimated) over whole WASP area 4987 km^2.
Atmospheric detection	Measure CO_2 in the atmosphere	By airplane or balloons	1	623,375	498,700	374,025	$50 per km^2 (estimated) over whole WASP area 4987 km^2.
Shallow Groundwater baseline and monitoring	CO_2 leakage into potable aquifers	Direct measurement of C species in groundwater obtained from drinking water wells	1	117,600	112,000	106,400	Analytical cost per sample $850 plus field work $150/sample = $1000 times # of samples.
Annual total cost during injection and the following 10 years				**740,975**	**610,700**	**480,425**	
Bi-annual total cost during injection and the following 10 years				**5,891,593**	**3,672,162**	**1,452,732**	
90 years after injection (annually)				**370,488**	**305,350**	**240,213**	

The cost for 4D seismic monitoring is included in Table 9. A 3D seismic survey is assumed to be conducted every second year during the fifty-year injection period and every fifth year for the ten years after injection stops. The cost will be higher for the other scenarios, since the area of the plume will be larger for each scenario.

Table 9: 4D seismic costs for vertical injection well scenario (without fracture stimulation).

	High (CAD)	Actual (CAD)	Low (CAD)	Source
Bi-annual total	26,179,939	21,816,616	13,089,969	$15,000–30,000 USD km^2, exchange rate 0.9, EPA (2008) equal plume size for each scenario.
10 years after injection (every fifth year)	52,359,878	43,633,231	26,179,939	
90 years after injection	–	–	–	

Other cost, such as project organization, well licenses and legal fees, is shown in Table 10. In addition, an equipment replacement cost of 2% of the total equipment cost is included annually.

Table 10: Other cost items for surface monitoring techniques.

	High (CAD)	Actual (CAD)	Low (CAD)	Source
Project organization during injection	861,466	717,888	646,099	4 FTE * $1920 h/year * 2.5 fully loaded FTE cost * hourly rate NOC code 2145 @ $43.45, 1 FTE NOC code 2254.
10 year after injection	180,461	150,384	135,346	10 year after injection.
90 year after injection	30,077	25,064	22,558	90 year after injection.
Licenses	16,000	4,000	2,000	Cost per well.
Legal fees per well	17,000	8,500	4,250	0.5% of injection well cost annually.

2. COST MODEL RESULTS

2.1 Cost Items

The total cost of the storage project is estimated to be between $0.7 billion CAD for the injection scenario with the ten vertical injection wells and $1.1 billion CAD for the injection scenario with the ten hydraulically fractured horizontal injection wells (see Table 11). All values in the table are shown in 2009 dollars. Table 11 shows that the vertical fractured scenario is more costly than the horizontal injection wells because of the 4D seismic costs relating to the size of the plume (see Figure 1). Table 1 also gives the total injection volume for the four scenarios, which is less than the results from the reservoir model. The small reduction in storage volume is caused by the assumption that there will be two new injector wells started each year and it will take five years before full injection is reached. Figure 1 gives the cost breakdown and shows that the largest expense for all scenarios is 4D seismic. The 4D seismic costs increases with plume size both in actual numbers and as a percentage of the total project cost (see Figure 2). With the suggested monitoring scheme, the cost of monitoring will make up approximately 75% of the project's total cost (Figure 2).

Table 11: Cost summary for the four scenarios including total cumulative injection.

Cost Item Groups	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Vertical ($1000 CAD)	Vertical Fracture Stimulated ($1000 CAD)	Horizontal ($1000 CAD)	Horizontal fracture stimulated ($1000 CAD)
Site planning and preparation	1,566	1,566	1,566	1,566
Injection well cost	13,862	14,569	27,538	31,738
Injection well operations	79,085	79,085	79,085	79,085
Well re-abandonment	3,108	3,108	3,108	3,108
Surface monitoring cost	162,090	162,090	162,090	162,090
4D seismic costs	316,341	512,171	466,979	647,746
Monitoring wells costs	11,187	11,187	11,187	11,187
Monitoring well operations	22,046	22,046	22,046	22,046
Equipment replacement	28,786	29,571	43,948	48,610
Surface lease and lease insurance	6,938	6,938	6,938	6,938
Project management, administration, and engineering	39,654	39,654	39,654	39,654
Total Cost	**684,662**	**881,984**	**864,138**	**1,053,767**

Cumulative Injectivity (Million Tons)	**200**	**309**	**282**	**391**

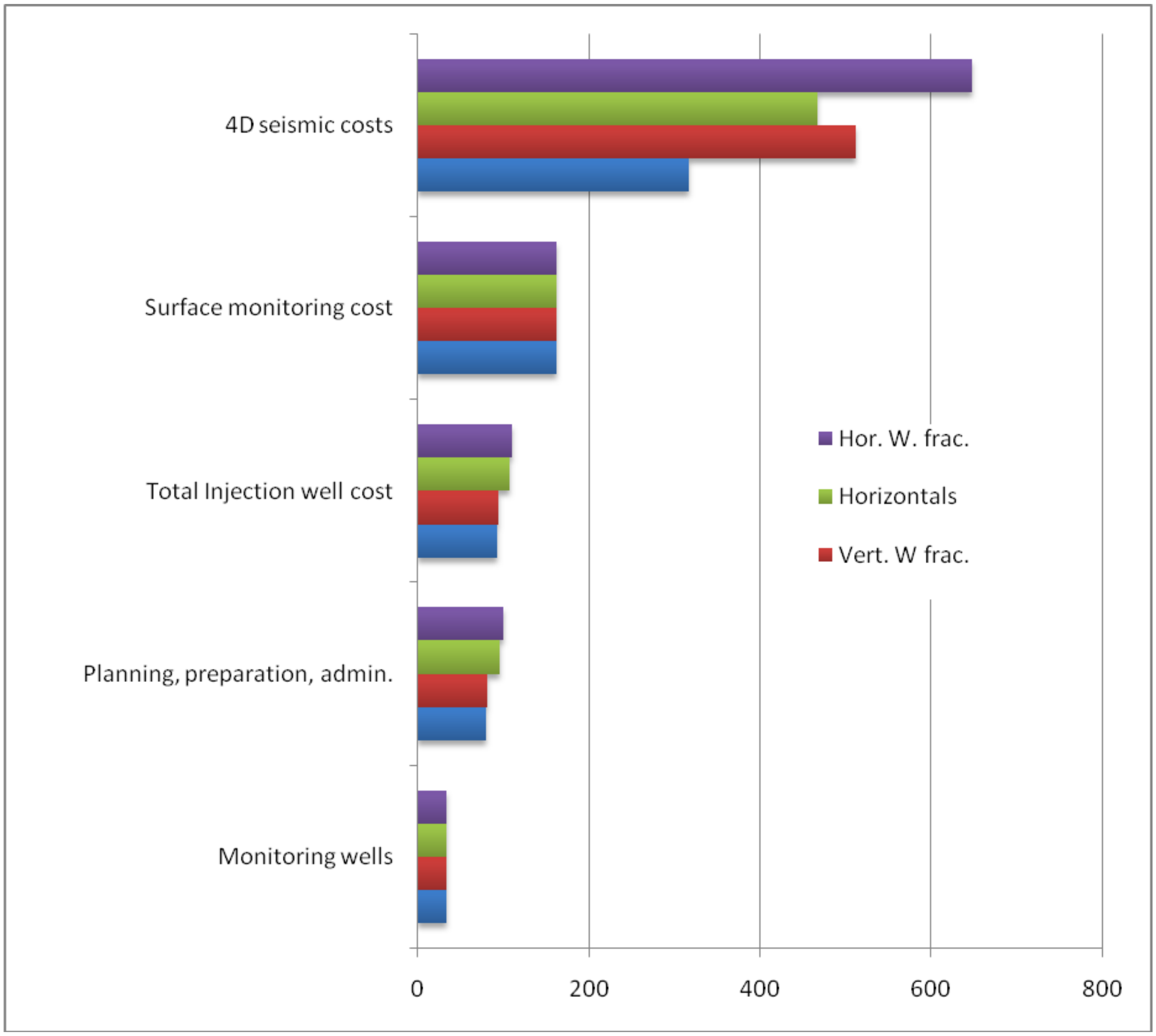

Figure 1: Comparison of different cost items for all four different scenarios.

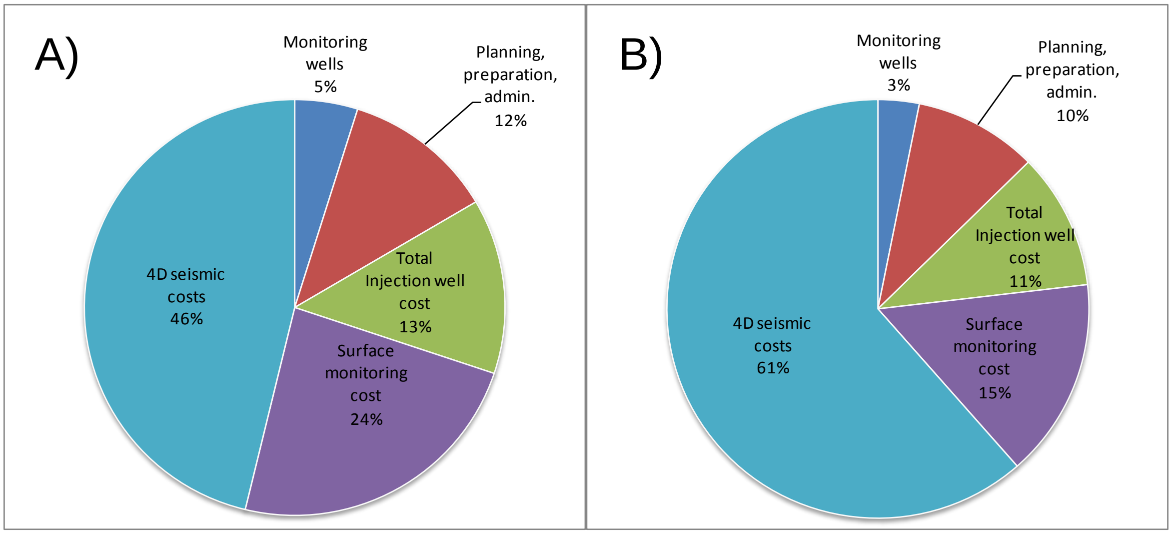

Figure 2: Comparison of different cost items for A) Vertical well without hydraulic fracturing stimulation (Scenario 1), and B) Horizontal wells with hydraulic fracturing stimulation (Scenario 4).

2.2 Monte Carlo Simulations

To estimate the cost per ton of CO_2 injection, Monte Carlo simulations were performed for all four scenarios. Figure 3 shows the results for the vertical scenario and indicates that the storage cost will be below \$3.55 CAD/ton (95 percentile) with a mean cost of \$3.38 CAD/ton of CO_2. A model with full co-variance between the cost items was also conducted, which gave a similar mean of \$3.35 CAD/ton of CO_2 and a larger spread of the 5 and 95 percentile results (\$3.92 CAD/ton of CO_2 for the 95 percentile). It is not expected that the different cost items will be correlated, since there are different driving mechanisms for the uncertainty in cost for the different cost items. Figure 4 shows the cost for the four different scenarios. The mean value varies from \$2.65 CAD/ton of CO_2 for the horizontal injection wells with hydraulic fracture stimulation to \$3.38 CAD/ton of CO_2 for the vertical injection wells scenario.

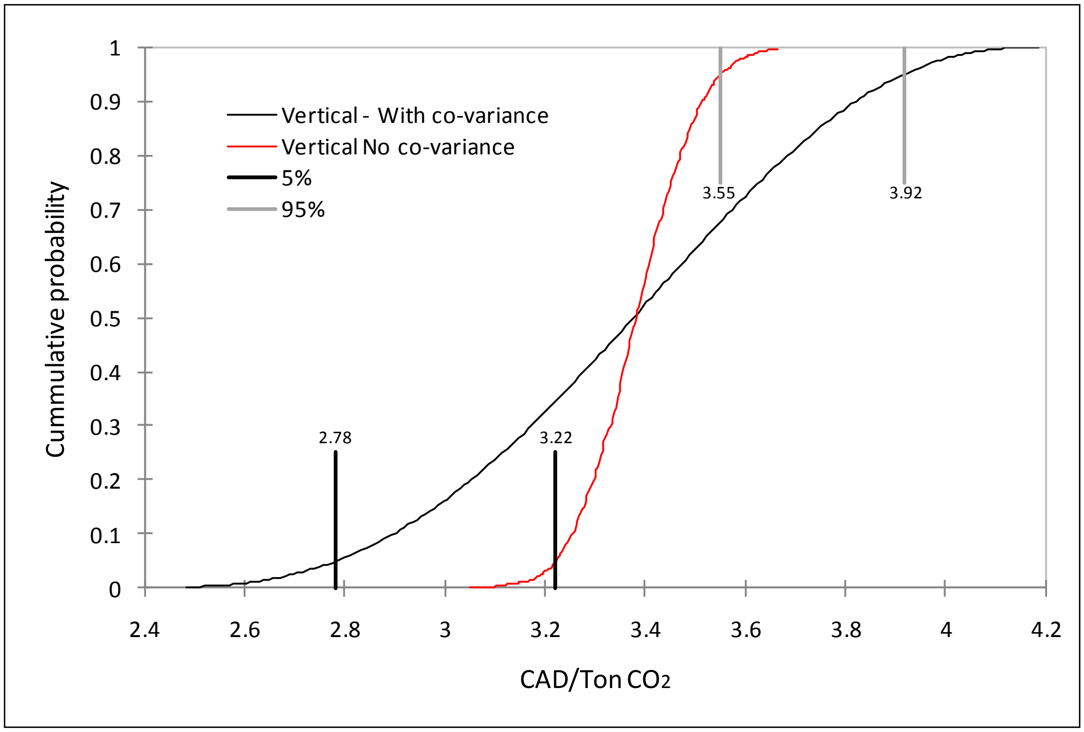

Figure 3: Cost per ton of stored CO_2 calculated based on Monte Carlo simulations for the vertical injection well scenario (Scenario 1).

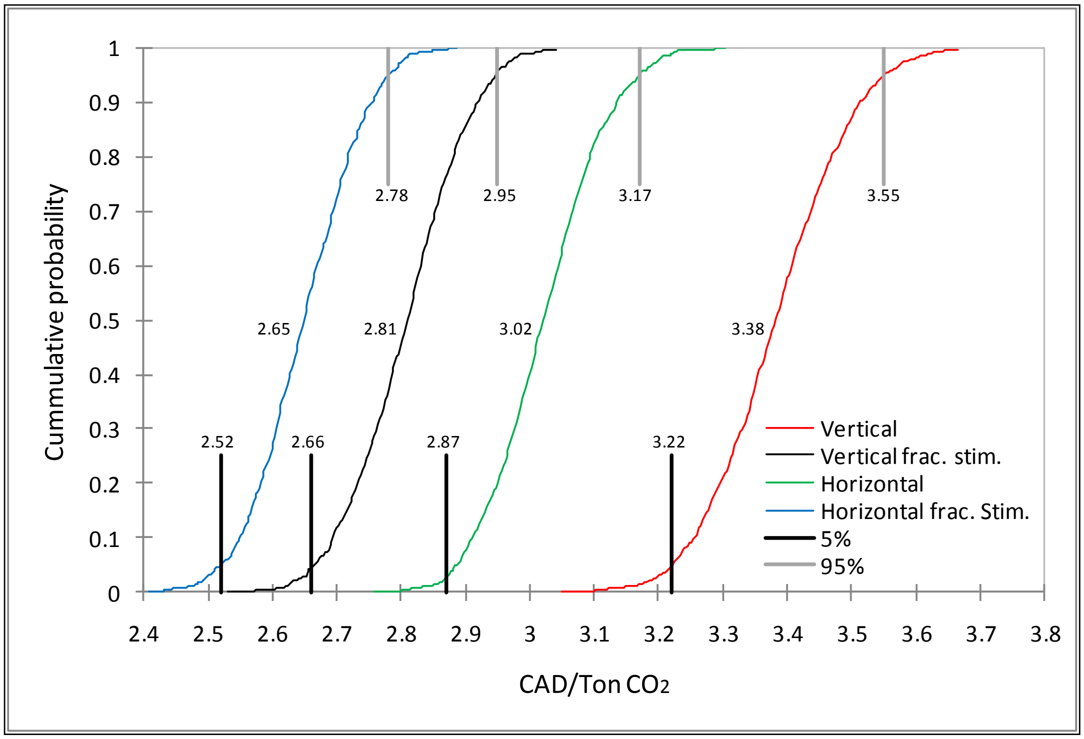

Figure 4: Cost per ton for stored CO_2 calculated using the Monte Carlo simulation method for all four scenarios.

CONCLUSION

A cost model for the Wabamun area CO_2 sequestration project was developed. From that model it was determined that the overall cost for the storage project was between $0.7 billion CAD for the injection scenario with ten vertical injection wells and $1.1 billion CAD for the injection scenario with 10 hydraulically fractured horizontal injection wells. All values are shown in 2009 dollars.

The mean cost for storing a ton of CO_2 was estimated to be in the range of $2.65 to $3.38 CAD/ton, which depends upon the configuration of the injection wells. The lowest cost per ton was the scenario with the largest amount of CO_2 stored.

In the cost model the highest cost was for monitoring at around 75% of the total cost, with the majority of the monitoring cost comprising 4D seismic. The high cost of repeatedly conducting seismic surveys questions the benefit of conducting the 4D seismic surveys.

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