Design and Optimization of a CO2 Pipeline Network for the Province of Alberta

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Abstract

Carbon Capture and Storage (CCS) represents a viable strategy to reduce greenhouse gas emissions into the atmosphere. Although CO2 capture accounts for 70% of the total cost of CCS, large-scale CCS projects have significant transportation costs. Therefore, there is a growing need to explore alternatives to reduce transportation costs. The goal of this project was to propose an optimized pipeline network capable of transporting 33 million tons of CO2 per year from 6 emission sources to adequately sized and characterized reservoirs (sinks) for sequestration within Alberta. The proposed 1200km-long pipeline network gathers CO2 from sources in Fort McMurray and transports it to the Nisku formation in central Alberta for storage. The sources connected in the pipeline network include the Canadian Natural Resources Horizon Oil Sands, Muskeg River Cogeneration Station, Shell Albian Oil Sands, Syncrude Mildred Lake Plant, Suncor Oil Sands, Suncor Firebag Oil Sands and Nexen Long Lake Oil Sands. Measures have been proposed to ensure that the pipeline is inherently safe. For example, the pipeline has been routed such that no highly-populated areas are traversed. The closest high-populated area is situated 1.5 km away from the pipeline network. CO2 dispersion modeling simulations indicate that this distance ensures no harmful impact on the occupants of these areas.

Keywords

Optimization, Pipeline Netweork, Carbon Dioxidey, Emission.

1. Introduction

Carbon capture and storage (CCS) is of major importance in this day and age as the world continues to increasingly focus on reducing greenhouse gas emissions with the goal of undermining its effects on global warming and climate change. For the foreseeable future, much of society's energy demands will continue to be met through the combustion of fossil fuels. Therefore, we must continue to make an effort to reduce the greenhouse gas emissions from the use of hydrocarbons.

More specifically, reduction in carbon dioxide emissions has been at the center of extensive scientific research. This is because carbon dioxide has been identified as the biggest contributor to GHG emissions [1]. Between 1999 and 2010, global carbon dioxide emissions increased from 22.7 billion tons to 33 billion tons [2]. Carbon Capture and Storage (CSS) represents a viable technique to help reduce CO2 emissions. It involves capturing, transporting in pipelines and storing CO2 in locations where it would not be emitted into the environment. CO2 can be used in Enhanced-Oil-Recovery to enhance oil production in wells reaching the end of their service life. CO2 can also be buried in saline formations, gas fields and coal seams. The transportation of CO2 from the source to sink is the major drawback of CCS. Unlike natural gas, there is a widespread perception that the transportation of CO2 is of low economic value. As of 2014, there were approximately 550,000 Km of natural gas pipelines versus 6,500 Km of CO2 pipelines [3].

For CCS to be meaningful it will be necessary to implement a pipeline network that transports a larger volume of CO2. One of the greatest potential for CO2 storage is in Alberta. In 2011, 25 Alberta facilities accounted for 78% of provincial emissions (96.4 Mt) [4]. Also in 2011, Canada emitted a total of 254.4 Mt of greenhouse gases, 48.5% of which was from Alberta. The province of Alberta has a goal to reduce Green House Gas (G H G) emissions by 50 Mt by the year 2020. It also has a goal to install 30 Mt of CCS capacity by the year 2020 and 139 Mt by 2050. The strategies they wish to employ in reaching their target involves applying energy efficient solutions, carbon capture and storage in appropriate geological locations and introducing cleaner methods for producing energy [5].

The main objective is to design and optimize a 33 Mt CO2 pipeline network for the province of Alberta, where design will be centrally focused on connecting a cluster of CO2 emission sources selected from those 25 sites (a higher priority will be placed on the larger producers of CO2) to suitable sinks within the province.

2. Pipeline Design Framework

2.1. Pipeline Routing

Each yellow marker in F represents a source (A-F) or sink (I-M). Fig has been included for a detailed view of the layout of the sources. To put in place a pipeline network joining together all sources and sinks, the system was divided into gathering and distribution. The connection of the sources at a central hub is defined as the gathering system and the delivery of CO_2 from the gathering hub to all the sinks is the distribution system. Selection of the optimal network for each subsystem was determined as follows:

- Generate candidate routes – In the case of the gathering system the intention was to connect the CO_2 sources to one gathering facility (alternatives shown in Figure 3). For the distribution system, CO_2 had to be delivered to every sink (alternatives shown in Figure 4).
- Size the pipeline segments using ASPEN Plus – A 2 psi/km pressure drop was adhered to for all segments.
- Use the McCoy and Parker pipeline network cost models to generate lower and upper bounds on the capital cost of each candidate route (shown in Table 1 for gathering and Table 2).
- Select the route primarily based on total cost.

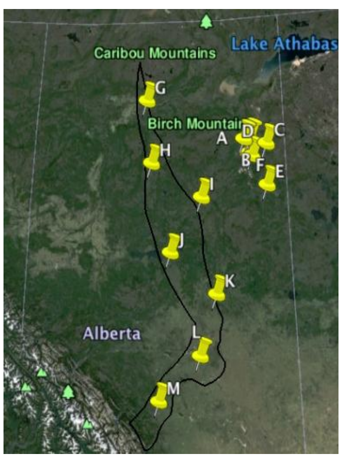

Figure 1. CO_2 Source and sink locations

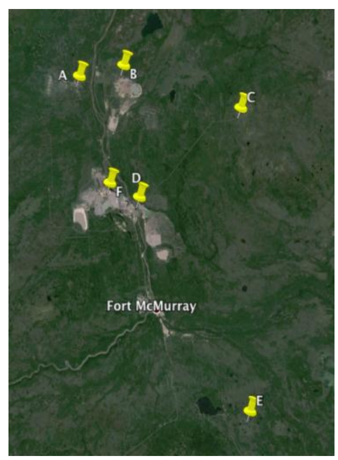

Figure 2. CO_2 source locations

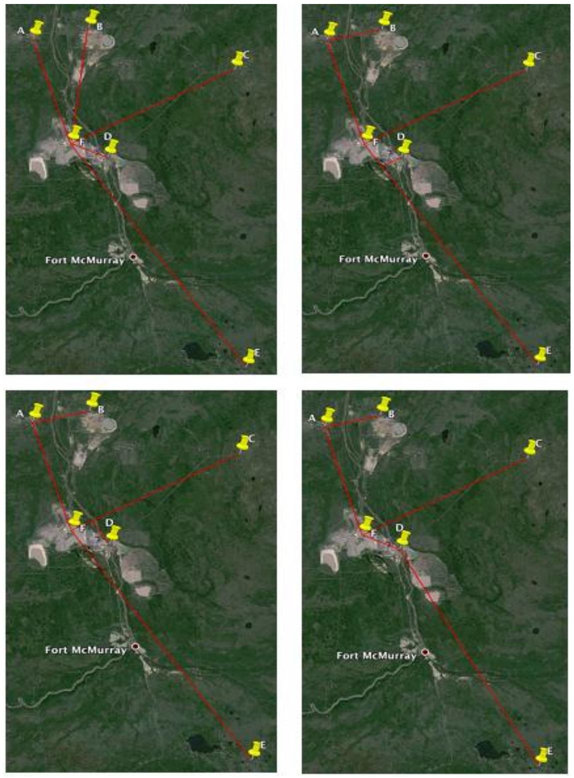

Figure 3**.** Alternate routes for the CO2 gathering system, joining together the 6 CO2 sources. From top left to bottom right: iteration A, B, C, D

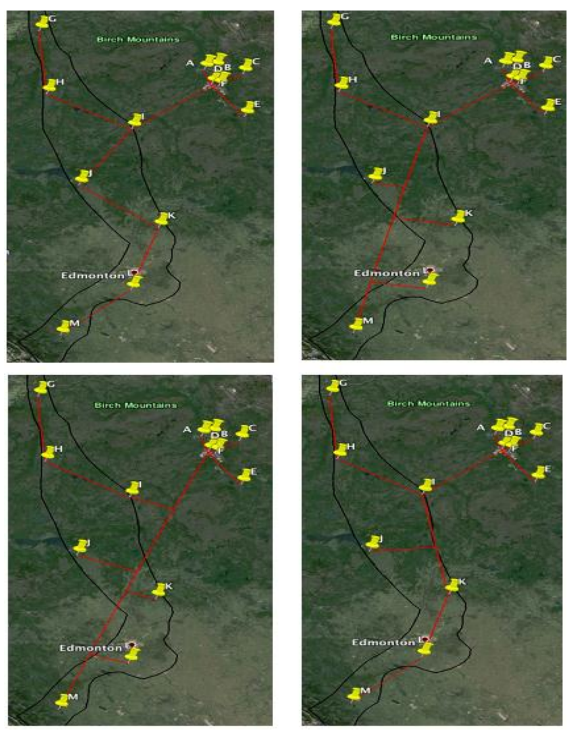

Figure. 4. Alternate routes for the CO2 distribution system joining, delivering CO2 to the 7 sinks within Wabanum Lake. From top left to bottom right: iteration E, F, G, H.

Having selected the network composed of the sub-systems shown in Figure 3a and Figure 4a, a visual inspection of all the terrain traversed by the segments was completed. The purpose of this was to identify any segments that could be re-routed to reduce the difficulties associated with construction and operation of the network. The main landmarks we were concerned with were densely populated areas and bodies of water.

The only segment identified that needed to be re-routed was that connecting distribution hub K to L. If built, this segment would be situated beneath the majority of Edmonton. A simple solution was to relocate distribution hub L to L' (shown in Figure 5) to avoid having to traverse beneath the city of Edmonton. As per the McCoy and Parker cost models, the distribution network increases in cost by $8 - $16 million as a result of the slightly longer segments from K to L' and L' to M. The reality is that this change in route would be significantly less costly than the former. Not only would it be very costly to install a pipeline beneath a city but additional costs would be incurred due to the much higher safety margins that would have to be guaranteed. The McCoy and Parker equations are defined in the following section.

Table 1. Cost estimate for the proposed gathering systems, iterations A-D, as per the McCoy and Rubin as well as Parker cost models

Iteration	McCoy and Rubin	Parker
A	$93,000,000.00	$146,000,000.00
B	$88,000,000.00	$137,000,000.00
C	$89,000,000.00	$139,000,000.00
D	$85,000,000.00	$134,000,000.00

Table 2. Cost estimates for the proposed distribution systems, iterations E, F, G, and H, as per the McCoy and Rubin as well as Parker cost models

Iteration	McCoy and Rubin	Parker
E	$533,000,000.00	$1,064,000,000.00
F	$581,000,000.00	$1,121,000,000.00
G	$584,000,000.00	$1,109,000,000.00
H	$550,000,000.00	$1,080,000,000.00

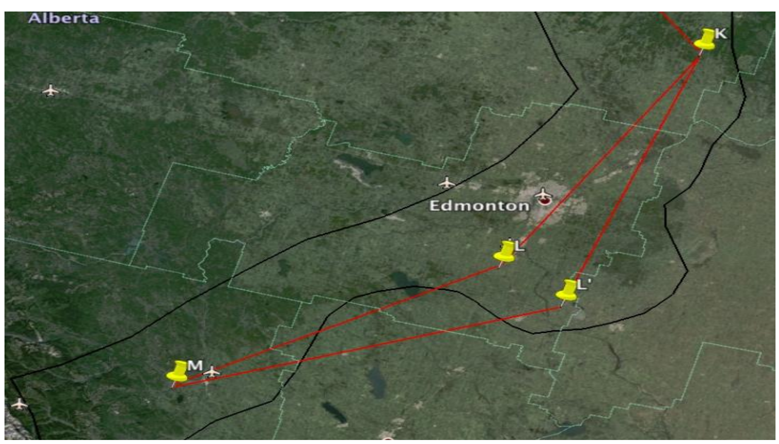

Figure**. 5.** Re-positioning sink L' in order to avoid placing a pipeline segment beneath Edmonton

The length and flow rate through each pipeline segment in the final design are shown in Table 6.

Table 3. Length and flow rate of each segment in the selected pipeline network

From	To	Flow Rate (kg/s)	Length (km)
A	F	110	33
B	F	75	36
C	F	148	48
D	F	253	11
E	F	130	82
F	I	1064	143
H	G	152	138
I	J	608	140
J	K	456	141
K	L	304	140
L	M	152	138
I	H	304	139

2.2. Pipeline Optimization

The optimization process presented below was carried out assuming that the CO_2 has been successfully captured and compressed into the dense phase. The optimization code was created in MATLAB to determine the optimal diameter and compressor work required to minimize the overall cost of the pipeline network. Consider a pipeline segment AB. The code will initially break the segment into two equal parts with a booster station in the center. The optimization code will return the optimal diameter of the 2 sub-segments and the work required to minimize the total cost of the pipeline. Thereafter, the code will break the segment AB into 3 equal sub-segments and repeat the process. The process will be carried out for a maximum of 5 sub-segments. The optimal solution of segment AB will be the number of sub-segments that yields the lowest total cost. Results indicate that the lowest cost is seen when the segment is divided into two equal parts (Figure 8). This methodology was then applied to all 12 pipeline segments in network. MATLAB's Genetic Algorithm was used to solve the optimization model. The genetic algorithm outputs a vector of the desired decision variables and the value of the objective function. The inputs to the genetic algorithm are the objective function, the number of decision variables, linear and non-linear constraints and also the lower and upper bound for all the decision variables.

The objective function for the optimization problem is a summation of pipeline capital cost, operating and maintenance cost and energy cost:

$$Total\ Cost = Cost_{capital} + Cost_{O\&M} + Cost_{Energy} \tag{6}$$

Capital costs can be further broken down into cost of the pipeline and the booster stations. Booster stations are placed on the mainline to provide minimal compression to the CO_2 already in the dense phase. Booster stations also referred to as pumps, are different from the internally geared compressors that are intended to pressurize gaseous CO_2 from 0.01MPa to 7.38 MPa at each source. The equation for capital cost is shown below:

$$Cost_{capital} = Cost_{pipe} + Cost_{booster} \tag{7}$$

The pipeline cost is dependent on the pipeline diameter, length, construction material and operating pressure. A weight-based model is initially used to estimate the material cost of the pipeline. Carbon steel, used as the material of construction, was assumed to have cost of 11 (US) $/kg.

$$Cost_{pipe} = \frac{11\pi\rho_p L\left(\left(D + t_p\right)^2 - D^2\right)}{4} \tag{8}$$

The pipeline thickness is not a decision variable in the objective function shown in equation (6) as it is solely dependent on maximum operating pressure. Pipeline thickness is given by the following equation:

$$Tt = \frac{P_{max} D}{2SFE} \tag{9}$$

McCollum and Ogden equation to determine the capital cost of booster stations is shown below:

$$Cost_{\ Booster} = \left(7.82W_p + 0.46\right) \times 10^6 \tag{10}$$

Work done on the fluid is given by the following equation:

$$W_p = \frac{\dot{m}(P_{out} - P_{in})}{\rho \eta_{booster}} \tag{11}$$

The operating and maintenance cost is catered towards the booster stations and pipeline line. It is expressed below:

$$Cost_{\ O\&M} = O\&M_{pipe} + O\&M_{booster} \tag{12}$$

McCollum and Ogden have shown that the annual operation and maintenance cost for the pipeline (US $/year) can be determined by:

$$O\&M_{pipe} = 120000 + 0.61(91398D + 0.899L - 259269) + 0.7(1547440D + 1.694L - 351355) + 24000 \tag{13}$$

While operating and maintenance cost for the booster stations is given by:

$$\mathrm{O\&M_{pipe}} = -176864\mathrm{W_p}^2 + 671665\mathrm{W_p} + 159292 \tag{14}$$

The cost of energy is dependent on the work done by the booster stations:

$$Cost_{Energy} = COE.\left(\sum_{i=1}^{N} W_{pi}\right).CF.8760 \tag{15}$$

The following hydrodynamic constraints were imposed on the objective function highlighted above:

1. The booster station increases the pressure of the inlet fluid. Therefore, the discharge pressure from the i^{th} booster station should be greater than the suction pressure:

$$\frac{p_{di}}{p_{si}} \geq 1 \tag{16}$$

2. To maintain the CO_2 in the dense phase, a minimum pressure of 8.6 MPa $\left(P_{si}^{min}\right)$ is required. Also, a maximum pressure of 15MPa (P_{di}^{max}) has been selected:

$$P_{si} \geq P_{si}^{min} \tag{17}$$

$$P_{di} \leq P_{di}^{max} \tag{18}$$

3. A minimum length and diameter of each pipeline segment has been selected for feasible solutions:

$$L_i \geq L_i^{min} \tag{19}$$

$$D_i^{max} \geq D_i \geq D_i^{min} \tag{20}$$

4. The summation of all pipeline sub-segments must equal the length of the pipeline segment:

$$\sum_{i=1}^{N+1}(L_i) = L_t \qquad (21)$$

5. The suction pressure into the i^{th} booster station is dependent on the discharge pressure from the $(i\text{-}1)^{th}$ booster station and the pressure loss across the previous segment of pipe:

$$P_{si+1} = P_{di} - \frac{2\rho f_{fi} v_i^2{}_{L_i}}{D_i} \qquad (22)$$

Where:

$$\frac{1}{2\sqrt{f_f}} = -2.01 log_{10}\left[\frac{\epsilon}{3.7D} - \frac{5.02}{Re} log_{10}\left[\frac{\epsilon}{3.7D} - \frac{5.02}{Re} log_{10}\left[\frac{\epsilon}{3.7D} + \frac{13}{Re}\right]\right]\right] \qquad (23)$$

Reynold's number (Re) is given by:

$$Re = \frac{4\dot{m}}{\pi\rho D^2} \qquad (24)$$

Given that this is a steady state analysis, the mass continuity equation for each pipeline segment holds. Hence:

$$m_{in} = m_{out} \qquad (25)$$

A key assumption made is that the simplified Bernoulli equation is applicable to CO_2 in the dense phase. This is because the density of dense-phase CO_2 does not vary significantly as opposed to gaseous CO_2. Hence, the density can be assumed to be constant within each pipeline segment. From Figure. 6. Pressure and Density Profile of Dense-phase Carbon Dioxide, it is evident that over 90 km a 10% reduction in density in observed. For this reason, dense-phase CO_2 can be approximated as an incompressible fluid.

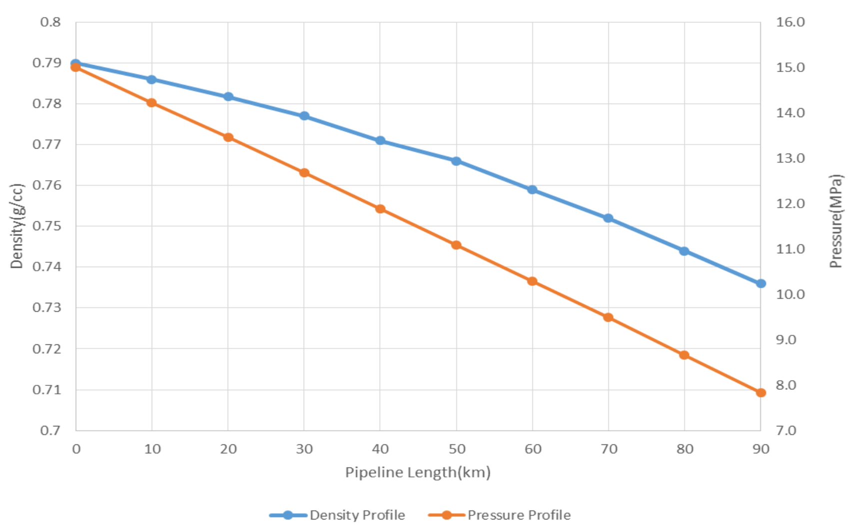

Figure. 6. Pressure and Density Profile of Dense-phase Carbon Dioxide in a carbon-steel pipe

It was also assumed that the pipeline network is planar and no elevation effects exist. For this reason, equation (22) does not account for elevation changes. It is also assumed that minor losses as result of fittings, bends and control valves are negligible. Considering that CO_2 is in the dense phase at pressures greater than 7.4MPa, calculations show that the minor losses are significantly less.

Consider the illustration below of a pipeline branch-in in the pipeline network with diameter of 0.4979 m and cross sectional area equal to 0.1938 m^2:

$$\dot{m}_A = 110kg/s \qquad \dot{m}_C = 185kg/s$$
$$v_A = 0.811m/ \qquad v_C = 1.364\ m/s$$

$$\dot{m}_B = 75kg/s$$
$$v_B = 0.553\ m/$$

The pressure drop between branch A and B, and A and C was estimated using the following equations respectively:

$$\Delta P_{AC} = \frac{\xi_A \rho v_c^2}{2} \tag{26}$$

$$\Delta P_{AB} = \frac{\xi_d \rho v_B^2}{2} \tag{27}$$

ξ_A and ξ_D are experimentally determined constants that are dependent on the fraction of flow in branch B, pipeline diameter and flow regime. The values of both parameters can be estimated from Figure 7. To read off the graph, the value of $\frac{G_A}{G_Z}$ has to be determined:

$$\frac{G_A}{G_Z} = \frac{\frac{75kg}{s}}{\frac{185kg}{s}} = 0.4$$

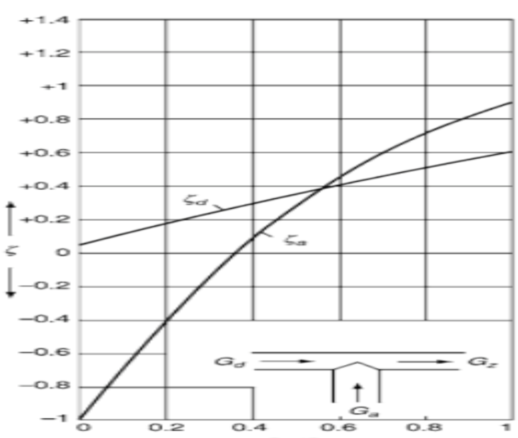

Figure. 7. Loss coefficient for Branch-in

ξ_A and ξ_D are approximately 0.3 and 0.1 respectively. Using equation (26) and (27) :

$$\Delta P_{AC} = \frac{0.3 * 800 * 1.364^2}{2} = 223Pa = 0.0002236MPa$$

$$\Delta P_{AC} = \frac{0.1 * 800 * 1.364^2}{2} = 74.4Pa = 0.000744MPa$$

Given that the lowest pressure across the pipeline is 8.6 MPa to keep CO_2 in the dense phase, minor losses due to branching, control valves, bends and fittings were neglected. As mentioned earlier, the code was applied to each segment of the pipeline network. The code is not capable of optimizing the entire network at once. The major inputs into the code are shown in Table 4.

Table 4**.** Major parameter inputs to MATLAB code

CO_2 Inlet Temperature(C)	25
CO_2 Inlet Pressure (MPa)	15
Booster Efficiency	0.75
Mass Flow rate of CO_2 (kg/sec)	Dependent on the segment being run
Outlet Pressure (MPa)	10
Minimum Pressure(MPa)	8.6
Maximum Pressure(MPa)	15
Minimum Length of sub-segment(Km)	Dependent on the segment being run
Diameter Lower limit (m)	Dependent on the segment being run
Diameter Upper limit (m)	Dependent on the segment being run

Table 5. Optimization results for the pipeline segments belonging to the gathering system

Start	End	Pump Work (MW)	Segment 1 Length (km)	Segment 2 Length (km)	Segment 1 Diameter (m)	Segment 2 Diameter (m)	Capital Cost (Parker Model)	Annual Operating Cost
A	F	0.0001	17	17	0.2439	0.2464	$26,527,453.67	$785,381.24
B	F	0.0001	18	18	0.213	0.2138	$26,084,899.86	$625,277.84
C	F	0.0001	24	24	0.2939	0.2917	$40,420,277.23	$1,072,531.99
D	F	0.0001	5.5	5.5	0.272	0.2714	$10,856,393.13	$860,467.56
E	F	0	41	41	0.3096	0.3082	$69,693,980.43	$1,250,106.05
						Total	**$173,583,004.33**	**$4,593,764.67**

Table 6. Optimization results for the pipeline segments belonging to the distribution system

Start	End	Pump Work (MW)	Segment 1 Length (km)	Segment 2 Length (km)	Segment 1 Diameter (m)	Segment 2 Diameter (m)	Cost (Parker Model)	Annual Operating Cost
F	I	0.0001	71.5	71.5	0.7731	0.7722	$305,715,742.23	$3,837,459.01
I	H	0.0001	70	70	0.4748	0.4751	$169,179,618.24	$2,276,301.55
H	G	0.0124	69.5	69.5	0.3633	0.3642	$131,917,254.70	$1,710,504.18
I	J	0.0191	70	70	0.6197	0.62	$226,849,713.10	$3,058,381.90
J	K	0.0002	70	70	0.556	0.5574	$200,212,058.39	$2,702,871.21
K	L'	0.1496	73	73	0.4799	0.4696	$178,010,045.77	$2,492,994.75
						Total	**$1,211,884,432.42**	**$16,078,512.60**

The minimum pressure was set at 8.6 MPa, to ensure that the CO_2 is always in the dense phase. To help set the upper and lower limits for diameter, simulations were done on Aspen. Based on a pressure drop rule of thumb of 2 psi/km an estimate of the segment diameter was deduced. The maximum pressure was set at 15 MPa based on the 900# flange rating. From the results of the optimization code, equipment such as compressors, flanges, and control valves will be sized.

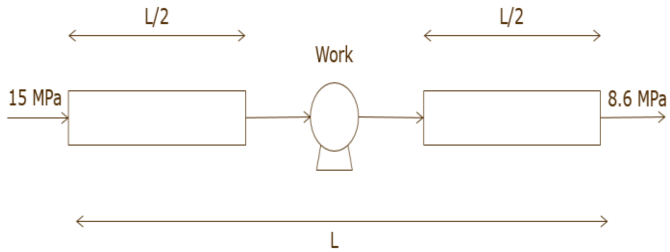

Figure. 8. Optimal Pipeline Configuration

The optimization results for the gathering and distribution systems are shown in Table 5 and Table 6, respectively. It is important to note that it is optimal in some pipeline segments not to pump the fluid. It can be observed in that for pipeline segment between E and F, no pump work is required.

A graphical illustration of the optimization carried out is seen in Figure 9. The curve indicates that the optimization process helps to select the optimal booster pump work and diameter to yield the lowest cost. Furthermore, a summary of the pipeline design specifications are shown in Table 7.

Table 7. Summary of Pipeline Design Specifications

Pipeline Design Specifications		
Pressure (MPa)	Design	15.5
	Maximum	15
	Minimum	8.6
Temperature (ºC)	35	
NPS	8-40	
Segment Length (km)	5.3-154	
Compression Work (MW)	Initial Compression	29-132
	Re-compression	0-0.19
Compressor	Integrally- geared	
Booster Pump	Multistage, axially split	
Burial Depth (m)	1 - 3	
Above ground Facilities	Initial compression, Isolation valves, pig launchers/receivers and booster stations	
Material	Carbon Steel	

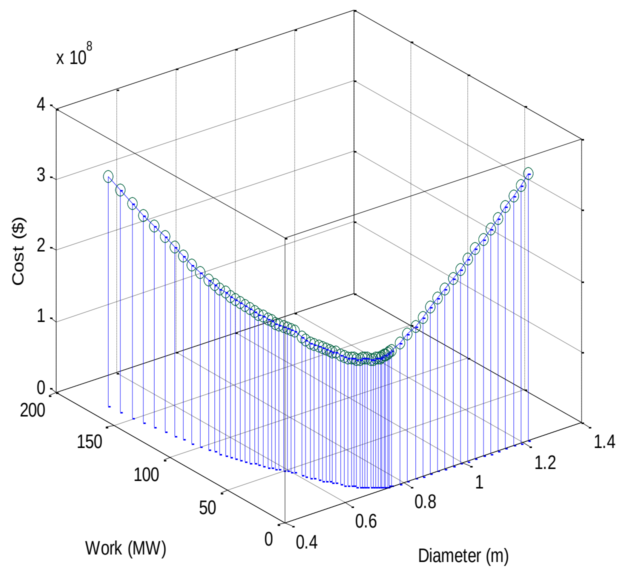

Figure. 9. Illustration of optimization for segment FI

The inlet pressure to every segment is set to 15 MPa and the outlet to 8.6 MPa. Therefore, in addition to the booster compressors in the middle of each line segment, additional compression is required from one segment to the next.

For example, the flows from facilities A to E arrive at facility F at a pressure of 8.6 MPa. Before entering the pipeline traversing from F to I, these flows must undergo re-pressurization to 15

MPa. The flow from facility F does not need to be recompressed in this case because it has just been compressed to 15 MPa in the initial compression. A description of the flows needing to be re-pressurized at specific nodes as well as work requirement and cost of equipment are detailed in Table 8.

2.3. Post Optimization Analysis

The network designed above is optimized for a flow rate of 1,064 kg/s. However, it is important to understand the ultimate capacity of this system. Although it meets current requirements, in order to move forward with such a large capital investment, it is necessary to confirm that the system will not be undersized within a short period of time.

Alberta carbon emissions are forecast to reach approximately 325 Mton/yr by 2030 [6]. Given that the six facilities involved in this project account for 12% of present day emissions, assuming that the proportion of emissions that they make up remains constant, it is forecast that the emissions from these facilities will reach a value of 39 Mton/yr in 2030. This translates into a pipeline flow rate of approximately 1,260 kg/s.

Table 8. Intermediate pump sizing

Node	Flow rate (kg/s)	Power requirement (kW)	Capital Cost	O&M Cost	Energy Cost
F	716	9,698.20	$14,584,076.39	$583,363.05	$3,642,923.62
I	608	8,235.34	$12,398,455.75	$495,938.23	$3,093,432.36
H	152	2,058.84	$3,170,279.72	$126,811.19	$773,358.09
J	456	6,176.51	$9,322,397.07	$372,895.88	$2,320,074.26
K	304	4,117.67	$6,246,338.40	$249,853.53	$1,546,716.17
L	152	2,058.84	$3,170,279.72	$126,811.19	$773,358.09
		Total	**$48,891,827.07**	**$1,955,673.09**	**$12,149,862.58**

Having implemented the optimized design detailed in the previous section in Aspen Plus, further analysis of the system was completed using the Sensitivity tool. The flow rate of CO_2 from each facility was varied up to a maximum total flow of 1,350 kg/s. In order to satisfy the constraints previously defined, the power at any pressurization facility was varied. Pipeline diameters were not adjusted because once installed, it would be very costly to go through the process of upsizing whereas pumps can simply be added in parallel to what is already installed. The additional compression requirements in order to make transportation of 1,350 kg/s of CO_2 feasible in the pipeline network detailed above are shown in Table 9.

Table 9. Additional compression requirements necessary to transport up to 1,350 kg/s of CO_2 through the optimized pipeline network

Flow (kg/s)	Additional compression requirement as compared to present work		Total Work in System (MW)
	Initial Compression	Booster Station	
1100	5%	12%	446
1150	7%	28%	470
1200	12%	40%	495
1250	16%	50%	521
1300	19%	58%	547
1350	22%	65%	574

Beyond a flow rate of 1,350 kg/s, the choking point is reached within some of the pipelines and the 15 MPa inlet and 8.6 MPa outlet constraint can no longer be upheld.

3. Conclusion

The main conclusion of this work is that the carbon tax needs to be increased to approximately $60/ton Co2 in order to make large scale CCS projects economically attractive. Beyond that, future work on this project involves completing a detailed design of the capture facilities and refining the network design completed to date.

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Biography

Ali Elkamel is Professor of Chemical Engineering at the University of Waterloo. He holds a BSc in Chemical Engineering and BSc in Mathematics from Colorado School of Mines, MS in Chemical Engineering from the University of Colorado-Boulder, and PhD in Chemical Engineering from Purdue University (West Lafayette), Indiana. His specific research interests are in computer-aided modelling, optimization and simulation with applications to energy production planning, sustainable operations and product design. He has supervised over 70 graduate students (of which 30 are PhDs) in these fields and his graduate students all obtain good jobs in the chemical process industry and in academia. He has been funded for numerous research projects from government and industry. His research output includes over 190 journal articles, 90 proceedings, over 240 conference presentations, and 30 book chapters. He is also a co-author of four books; two recent books were published by Wiley and entitled Planning of Refinery and Petrochemical Operations and Environmentally Conscious Fossil Energy Production.