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CO2 Transportation Cost Calculations:

When estimating the cost for a pipeline several technical features of the pipeline must be provided or estimated to determine the diameter, length and allowed pressure drop for a given mass flowrate of CO_2. Once these parameters are defined, then capital and operating costs for the pipeline can be estimated. The following information should only be used to find rough estimates and should not be relied on to make technical or economic decisions.

A. **Estimating the Pipe Diameter**:

There are several equations which can be used to estimate the hydraulic performance of a pipeline. In addition, there is one study which used advanced pipeline modeling software to estimate pipe diameters for a given mass flows of CO_2 and pipeline length. An interpolation of this data is possible and it can be represented by an equation to approximate the appropriate diameters for a given mass flow and pipe length. There are three equations described here to estimate the diameters of CO_2 pipelines. None of them account for changes in altitude.

1. MIT Formula:

Several MIT [1,2] reports related to CO_2 pipeline cost estimation, report the following standard hydraulic equation:

$$(P_1-P_2) = 32Lfm^2 / (\pi^2\rho D^5)$$

Where:

P_1 and P_2 are the pressures in Pascals at the beginning and end of the pipe
L is the length of the pipe in metres
f is the Fanning friction factor
m is the mass flow rate in kg/s
ρ is the density in kg/m^3
D is the diameter in metres

Assumptions:

P_1 is assumed to be about 2,000 psi or 14,000 kpa.
P_2 is limited to 10,000 kpa or about 1,450 psi to maintain CO_2 as a fluid.
f is estimated [3] by $(1 / (4 \times \mathrm{Log}(D/E) +2.28\ )^2$
E here [5] is defined as the roughness of the material in m = .000457
ρ the density [2] is estimated as 884 kg/m^3

The equation described above can be rearranged to solve for the diameter of a pipeline. That equation is

$D = (32Lfm^2 / [(P_1-P_2)\pi^2\rho])^{.2}$

2. Carnegie Institute of Technology formula:

Carnegie Mellon University [4,5] has published two documents with equations which can be used to estimate the diameter of a pipeline:

$$D = (-64ZRTfm^2L / [\pi^2M(P_2^2-P_1^2)])^{.2}$$

Where:

Z is the compressibility defined as $PM/\rho RT$

Where $P = 2/3(P_2+P_1-P_2P_1/[P_2+P_1])$
M= Molecular weight
ρ is the density in kg/m^3
R=8.3145
T= Temperature in kelvin

Other values are the same as those listed above. There is a version of this equation which includes the effect of altitude.

3. WorleyParsons:

WorleyParsons [6] published a report for the Austrian government on the estimated sizing of CO_2 pipelines given distances and mass flow rates. They used the Aspen HYSYS model version 6.5 with the PIPESYS extension. The data supplied can be approximated by the $D = (7.7+.009L)m^{.38}$ where diameter here is in inches. Generally the estimated diameter is rounded up to the next largest standard pipe size.

	Km	200	400	600	800	1000
Diameter (in)	5	16	18	20	22	22
	10	22	24	26	28	30
	15	24	28	30	32	34
	20	28	32	34	36	38
	25	30	34	38	40	40
	30	32	36	40	42	44
	35	34	38	42	44	46
	40	36	40	44	46	48

B. **Estimating the Cost of a CO2 Pipeline**:

Most of the information available is based on the costs to construct and operate natural gas pipelines. This data has in some cases been adjusted to account for the cost of supplying CO_2 and to account for inflation. Two sources for the cost of CO2 are considered here: i) cost estimates used by the National Energy Technology Laboratory (NETL) and ii) recent cost information reported in the Oil and Gas Journal.

1. <u>NETL Capital Cost Estimates</u>:

NETL [7] has established an approach to estimate several components of the capital cost of a CO2 pipeline. These equations were originally developed by the University of California[8]. The original equations were modified to include escalation to bring the costs to June-2007 year dollars.

Materials = 64,632 + 1.85L(330.5D^2 + 686.7D + 26,960)
Labour = 341,627 + 1.85L(343.2D^2 + 2,074D 170,013)
Misc = 150,166 + 1.58L(8,417D + 7,234)
Right of Way = 48,037 +1.2L(577D + 29,788)
CO2 Surge Tank = 1,150,636
Pipeline Control System = 110,632

Where D is diameter in inches and L is in miles.

This study also provided rough estimates for the costs of pipelines for various terrains. See citation 9 as well.

	Kinder-Morgan ($/inch/mile) [7]	Cost Multiplier [9]
Flat, Dry	$50,000	1.0
Mountainous	$85,000	2.5
Marsh, Wetland	$100,000	
River	$300,000	
High Population	$100,000	
Offshore (150’-200’depth)	$700,000	
Desert		1.3
Forest		3.0
Offshore (< 500m depth)		1.6
Offshore (>500m depth)		2.7

2. <u>Oil and Gas Journal Information</u>:

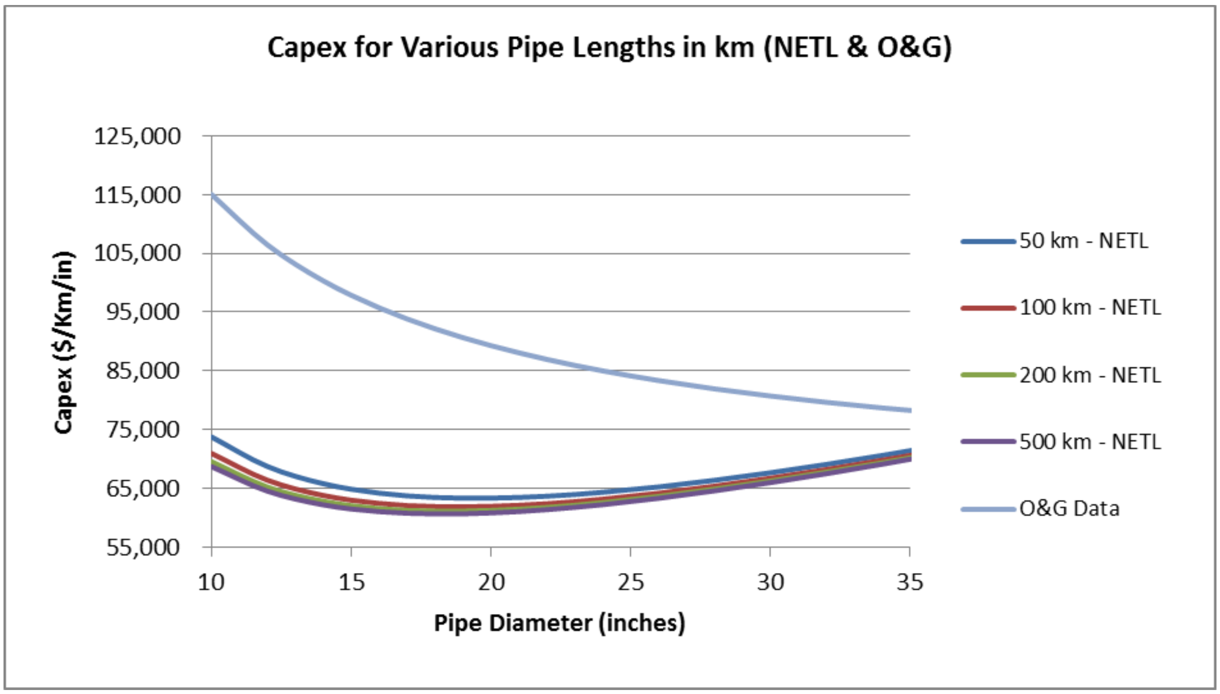
The November 1, 2010 Oil and Gas Journal published costs for natural gas pipelines over the past decade. The data supplied in table 6 shows costs for various components for pipe sizes for each of the past 10 years. The data is in $/mile. Data for 2010 was either taken from table 6 or estimated based on costs for previous years. It was used to determine costs in $/km-in. Regressions were completed on the data to determine linear equations to estimate costs in $/km-in for several pipeline costs components.

ROW = L*(893*D+10,800)

Materials = L*(22,800*D +14,480)
Labour = L*(26,390*D +203,000)
MISC = L*(13,500*D +286,000)

The data suggests that the cost of pipelines have doubled compared to the costs in 2008 and 2009 and increased by a factor of 4 since 2006. However, various terrains are included in these values which may make them difficult to compare against the base case costs.

The following graph shows who the NETL cost estimates compare with the data provided in the Oil and Gas Journal for diameters between 10 and 30 inches.



C. **<u>Collectors</u>**:

CO_2 will likely be collected by a series of pipes and then moved to a large pipe system. If one assumes that there will be a certain number of collectors, each with the same length and diameter, one can use the previous equations to solve for the diameter of each collector. This data can then be put through the cost equations above to solve for the capital costs of this collector system.

D. **<u>O&M</u>**:

O&M for a given year is generally expressed as a percentage of the installed capital costs. That cost is assumed to be about 3 to 5%.

E. **Tolls**:

A rough estimate of a pipeline toll can be found by taking the capital cost and multiplying by a capital recovery factor plus 5% for O&M and dividing these costs by the volume of CO_2 moved in a given year.

F. **Compression**:

The mass flow rate in a given pipeline can be increased by adding booster compressors. If one assumes how much additional mass flows one wants to move, one can calculate the pressure drop associated with the new mass flow rate. If it exceeds the maximum allowable pressure drop then boosting compression is required. A boosting compressor is assumed to increase the pressure by no more than the maximum allowed pressure drop. If the mass flow increase is substantial then several compressors will be required.

Cost estimates for booster compressors are based on booster power estimates. Booster power can be estimated by volumetric flow rate X pressure increase / efficiency of booster [(9)]. Citation 9 suggests that the cost of compression is about $6 million per MW of power installed. The Oil and Gas Journal reported compression costs for a survey of projects build over the previous year. The cost was about $2,600/hp. This translates into about $3.5 million/MW. The cost of compression would also include the power required to operate the booster as well.

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