An engineering-economic model of pipeline transport of CO₂ with application to carbon capture and storage

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1. Introduction

Large reductions in carbon dioxide (CO₂) emissions from energy production will be required to stabilize atmospheric concentrations of CO₂ (Hoffert et al., 1998, 2002; Morita et al., 2001). One option to reduce CO₂ emissions to the atmosphere is CO₂ capture and storage (CCS); i.e., the capture of CO₂ directly from anthropogenic sources and sequestration of the
CO₂ geological sinks for significant periods of time (Bachu, 2003). CCS requires CO₂ to be captured from large-scale industrial processes, compressed to high pressures, transported to a storage site, and injected into a suitable geological formation where it is sequestered and kept from the atmosphere. Studies indicate that under appropriate policy regimes, CCS could act as a potential “bridging technology” that would achieve significant CO₂ emission reductions while allowing fossil fuels to be used until alternative energy sources are more widely deployed. Moreover, as part of a portfolio of emissions reducing technologies, CCS could substantially reduce the cost of achieving stabilization goals (Herzog et al., 2005).

CCS will have significant impacts on the cost of electricity production and costs in other potential applications. Thus, methods are required to estimate the costs of CCS to evaluate actions and policies related to the deployment of CCS projects. In the last decade the understanding of CCS technologies has increased greatly, as reflected by the recent IPCC Special Report on Carbon Dioxide Capture and Storage (Metz et al., 2005). However, there are still significant gaps in knowledge of the cost of integrated capture, transport, and storage processes. For example, many studies of carbon capture processes have been undertaken (Thambimuthu et al., 2005) and engineering-economic models linking process cost to key engineering parameters have been developed (Rao and Rubin, 2002), but the majority have not yet been linked with transport and storage models to determine the cost of an integrated CCS process. Most cost studies either exclude transport and storage costs or assume a constant cost per tonne of CO₂ in addition to capture costs (Metz et al., 2005).

There have been few studies that have addressed the cost of CO₂ transport and storage in detail. However, earlier work by Svensson et al. (2004) identified pipeline transport as the most practical method to move large volumes of CO₂ overland and other studies have affirmed this conclusion (Doctor et al., 2005). Therefore, this paper focuses on the cost of CO₂ transport via pipeline. Skovholt (1993) presented rules of thumb for sizing of CO₂ pipelines and estimated the capital cost of pipeline transport. In 2002, the International Energy Agency Greenhouse Gas Programme (IEA GHG) released a report that presented several correlations for the cost of CO₂ pipelines in Europe based on detailed case study designs (Woodhill Engineering Consultants, 2002). More recently, an engineering-economic CO₂ pipeline model was developed at the Massachusetts Institute of Technology (MIT) (Bock et al., 2003). Results from these and similar studies were summarized in the recent IPCC report (Doctor et al., 2005). However, none of these studies considered the unusual physical properties of CO₂ at high pressures (Fesmire, 1983), the realities of available pipeline diameters and costs, or regional differences in the cost of CO₂ transportation.

The objective of this paper is to estimate the cost per tonne of transporting CO₂ for a range of CO₂ flow rates (e.g., reflecting different power plant sizes) over a range of distances, and to also incorporate regional cost differences within the continental US. These cost estimates are embodied in an engineering-economic model that will be presented in this paper. A probabilistic analysis is used to quantify the impact of uncertainty and variability in cost model parameters on CO₂ transport cost. This analysis also shows the range of costs associated with a given project and the probability of a given cost for a specific scenario.

2. Properties of CO₂ in pipeline transport

Efficient transport of CO₂ via pipeline requires that CO₂ be compressed and cooled to the liquid state (Zhang et al., 2006). Transport at lower densities (i.e., gaseous CO₂) is inefficient because of the low density of the CO₂ and relatively high pressure drop per unit length. Moreover, by operating the pipeline at pressures greater than the CO₂ critical pressure of 7.38 MPa, temperature fluctuations along the pipeline will not result in the formation of gaseous CO₂ and the difficulties encountered with two-phase flow (Recht, 1984).

The properties of CO₂ are considerably different from other fluids commonly transported by pipeline, such as natural gas. Thus, it is necessary to use accurate representations of the phase behavior, density, and viscosity of CO₂ and CO₂-containing mixtures in the design of the pipeline. The results presented here are based on the physical properties (i.e., density and phase behavior) of CO₂ and CO₂-containing mixtures calculated using a cubic equation of state with Peng–Robinson parameters, and mixing rules employing a binary interaction parameter (Reid et al., 1987). The transport properties of CO₂ have been estimated using the Chung et al. (1988) method, extended to high pressures by Reid et al. (1987).

Fig. 1 shows that the compressibility of CO₂ is non-linear in the range of pressures common for pipeline transport and is highly sensitive to any impurities, such as hydrogen sulfide (H₂S). Fig. 1 also shows the significant difference between the compressibility of pure CO₂ and CO₂ with 10 vol. % H₂S. To reduce difficulties in design and operation, it is generally recommended that a CO₂ pipeline operate at pressures greater than 8.6 MPa where the sharp changes in compressibility of CO₂ can be avoided across a range of temperatures that may be encountered in the pipeline system (Farris, 1983). Conversely, line-pipe with ASME-ANSI 900# flanges has a maximum allowable operating pressure of 15.3 MPa at 38 °C (Mohitpour et al., 2003). Operating the pipeline at higher pressures would require flanges with a higher rating. Over the range of typical conditions shown in Fig. 1, the density of CO₂ varies between approximately 800 and 1000 kg/m³.

Operating temperatures of CO₂ pipelines are generally dictated by the temperature of the surrounding soil. In northern latitudes, the soil temperature varies from a few degrees below zero in the winter to 6–8 °C in summer, while in tropical locations; the soil temperature may reach up to 20 °C (Skovholt, 1993). However, at the discharge of compression stations after-cooling of compressed CO₂ may be required to ensure that the temperature of CO₂ does not exceed the allowable limits for either the pipeline coating or the flange temperature.

3. Pipeline performance model

While there are proven flow equations available for use with high pressure gas pipelines (e.g., AGA fully turbulent equation),
these equations can introduce error into the estimation of flow rates in liquid CO₂ due to the underlying assumptions made in their development (Farris, 1983). The pipeline performance model used here is based on an energy balance on the flowing CO₂, where the required pipeline diameter for a pipeline segment is calculated while holding the upstream and downstream pressures constant. The mechanical energy balance can be written as (Mohitpour et al., 2003):

\[
\frac{c}{v} du + \frac{1}{v} dp + \frac{d}{v^2} dh + 2 \frac{f c^2}{D_i} dL = 0
\]

where \(c\) is a constant equal to the product of density, \(\rho\) (kg/\(m^3\)), and fluid velocity, \(u\) (m/s); \(g\) is acceleration due to gravity (m/s\(^2\)); \(v\) is the specific volume of fluid (m\(^3\)/kg); \(p\) is pressure (Pa); \(h\) is height (m); \(f\) is the fanning friction factor; \(D_i\) is the internal pipeline diameter (m); \(L\) is the pipeline segment length (m).

The energy balance given in Eq. (1) can be simplified by assuming that changes in kinetic energy of the flowing CO₂ are negligible (constant velocity), and that the compressibility of the CO₂ or CO₂-containing mixture can be averaged over the length of the pipeline. The resulting energy balance, as derived by Mohitpour et al. (2003), and solved for pipe segment diameter:

\[
D_i = \left\{ \frac{-64 Z_{ave} R^2 T_{ave} f c^2 L}{\left[ \pi^2 (M Z_{ave} T_{ave}) (p_2^2 - p_1^2) + 2 g Z_{ave} M^2 (h_2 - h_1) \right]} \right\}^{1/5}
\]

where \(Z_{ave}\) is the average fluid compressibility; \(R\) is the universal gas constant (Pa m\(^3\)/mol K); \(T_{ave}\) is the average fluid temperature (K); \(m\) is the design mass flow rate (kg/s); \(M\) is the molecular weight of the stream (kg/kgmol); \(p\) is pressure at points 1 and 2, which are upstream and downstream, respectively; \(h\) is the pipeline elevation, where 1 and 2 represent upstream and downstream locations.

Fort the case of a CO₂ pipeline modeled here, the average temperature, \(T_{ave}\), is assumed to be constant at ground temperature so that \(T_{ave} = T_{ground}\). Because pressure varies non-linearly along the pipeline, the average pressure, \(P_{ave}\), required in Eq. (2) is calculated (Mohitpour et al., 2003):

\[
P_{ave} = \frac{2}{3} \left( \frac{p_2 + p_1}{p_2 + p_1} \right)
\]

Thus, Eq. (2) can be used to calculate the pipe diameter required for a given pressure drop. Complicating this, however, is the Fanning friction factor, which is a function of the pipe diameter. The Fanning friction factor cannot be solved for analytically; however, an explicit approximation for Fanning friction factor is given by Eq. (4) (Zigrang and Sylvester, 1982):

\[
\frac{1}{2 \sqrt{f_f}} = -2.01 \log \left\{ \left( \frac{c}{D_i} \right)^{3.7} \left( \frac{5.02}{\beta_f} \log \frac{c}{D_i} \right)^{3.7} - \left( \frac{5.02}{\beta_f} \log \frac{c}{D_i} \right) \right\}
\]

where \(c\) is the roughness of the pipe (m), which is approximately 0.0457 mm for commercial steel pipe (Boyce, 1997), and \(\beta_f\) is the Reynolds number, which is defined as (McCabe et al., 1993):

\[
Re = \frac{4m}{\mu \pi D_i}
\]

where \(\mu\) is the viscosity of the fluid (Pa s). As a result, Eqs. (2), (4), and (5) must be solved iteratively to determine the pipe diameter required for a particular application. In the iteration scheme shown in Fig. 2, the Reynolds number, Eq. (5), is first calculated using an initial estimate of pipe diameter based on a velocity of 1.36 m/s. This initial velocity is representative of CO₂ pipeline flows, and thus minimizes the number of iterations required over a range of model inputs for both design mass flow rate and pipeline length. The calculated Reynolds number is then used in Eq. (4) to estimate the Fanning friction factor, which is then substituted into Eq. (2). This yields an updated diameter, which is compared with the value at the previous iteration. Values for the internal diameter converge to within 10\(^{-6}\) m in generally less than five iterations.

Line pipe is not available in continuous diameters. Thus the internal pipe diameter calculated must be adjusted to account for both available pipe diameters and the pipe wall thickness. A discrete size of line pipe is frequently referred to by its Nominal Pipe Size (NPS), which corresponds approximately to the outside pipe diameter measured in inches. In the model presented here, eleven NPS values between 4 and 30 are available. To determine the inside diameter, the pipe wall thickness (also known as the pipe schedule) for each NPS is estimated using the method specified in the US Code of Federal Regulations (CFR), which regulates the design, construction, and operation of CO₂ pipelines in the United
The pipe wall thickness, \( t \), in meters is given as (CFR, 2005):

\[
   t = \frac{p_{\text{mop}} D_o}{2SEF}
\]  

where \( p_{\text{mop}} \) is the maximum operating pressure of the pipeline (Pa), \( D_o \) is the outside pipe diameter (m), \( S \) is the specified minimum yield stress for the pipe material (Pa), \( E \) is the longitudinal joint factor (reflecting different types of longitudinal pipe welds), and \( F \) is the design factor (introduced to add a margin of safety to the wall thickness calculation). For the purposes of estimating the pipe wall thickness, the maximum operating pressure is assumed to be 15.3 MPa, the longitudinal joint factor is 1.0, and the design factor is 0.72 (as required in the CFR). The minimum yield stress is dependent on the specification and grade of line pipe selected for the pipeline. For \( CO_2 \) service, pipelines are generally constructed with materials meeting American Petroleum Institute (API) specification 5L (American Petroleum Institute, 2004). In this case, the minimum yield stress has been specified as 483 MPa, which corresponds to API 5L X-70 line pipe.

The value of \( D_i \), calculated from Eq. (2) is adjusted to the next largest value of \( D_i \) for an available NPS. Based on the adjusted \( D_i \), the adjusted downstream pressure for the pipeline segment is calculated. This pressure will always be greater than the downstream pressure specified by the user since the adjusted diameter will always be greater than the optimum value calculated by Eq. (2).

Fig. 3 shows the NPS of a pipeline carrying pure \( CO_2 \) as a function of the design \( CO_2 \) mass flow rate, as calculated by the iteration scheme shown in Fig. 2. For fixed inlet pressure and minimum outlet pressure, the required pipe diameter increases with increasing design \( CO_2 \) flow rate and pipeline distance. Steps in pipeline diameter occur because of the discrete NPS available in the model. For example, the model estimates an internal diameter of 0.38 m for a pipeline spanning a distance of 100 km designed to carry 5 million tonnes per year of \( CO_2 \) at a pressure drop of 35 kPa/km. However, this is not a common line pipe size; thus, the next largest NPS is selected.
by the model, which has an internal diameter of about 0.39 m.

4. Pipeline cost model

Detailed construction cost data for actual CO₂ pipelines (i.e., as-built-cost including the length and diameter) are not readily available; nor have many such projects been constructed in the last decade (Doctor et al., 2005). For these reasons, the data set used to develop the pipeline capital cost models is based on natural gas pipelines. However, there are many similarities between transport of natural gas and CO₂. Both are transported at similar pressures, approximately 10 MPa and greater. Assuming the CO₂ is dry, which is a common requirement for CCS, both pipelines will require similar materials. Thus, a model based on natural gas pipelines offers a reasonable approximation for a preliminary design model used in the absence of more detailed project-specific costs.

The CO₂ pipeline capital cost model is based on regression analyses of natural gas pipeline project costs published between 1995 and 2005 (True, 1995, 1996, 1997, 1999, 2000a,b, 2001, 2002, 2003a,b; True and Stell, 2004; Smith et al., 2005). These project costs are based on Federal Energy Regulatory Commission (FERC) filings from interstate gas transmission companies. The entire data set contains the “as-built” costs for 263 on-shore pipeline projects in the contiguous 48-states and excludes costs for pipelines with river or stream crossings as well as lateral pipeline projects (i.e., a pipeline of secondary significance to the mainline system, such as a tie-in between the mainline and a power plant). Costs from each year’s projects have been adjusted to 2004 dollars using the Marshall and Swift equipment cost index (Chemical Engineering, 2006).

The total construction cost for each project is broken down into four categories: materials, labor, right-of-way (ROW), and miscellaneous charges. The materials category includes the cost of line pipe, pipe coatings, and cathodic protection. Labor is the cost of pipeline construction labor. ROW covers the cost of obtaining right-of-way for the pipeline and allowance for damages to landowners’ property during construction. Miscellaneous includes the costs of surveying, engineering, supervision, contingencies, telecommunications equipment, freight, taxes, allowances for funds used during construction (AFUDC), administration and overheads, and regulatory filing fees.

Separate cost models have been developed for each of the cost categories. The capital cost models take this general form:

$$\log(C) = a_0 + a_1\text{NE} + a_2\text{SE} + a_3\text{CL} + a_4\text{SW} + a_5\text{W} + a_6\log(L) + a_7\log(D_{nps})$$

(7)

where NE, SE, CL, SW, and W are binary variables reflecting the five geographic regions besides Midwest (i.e., Northeast, Southeast, Central, Southwest, and West, respectively) that take a value of 1 or 0 depending on the region and increase or decrease the estimated cost relative to the Midwest value. C is the pipeline capital cost in 2004 US dollars. The variable L is the total pipeline length in kilometers, and the D is the pipeline NPS. Regional variables exist in the cost model only if they are statistically significant predictors of the cost; thus different cost-component models include different sets of regional variables.
There are several properties of Cobb-Douglas functions that
adjusted-constant means that multiplying both the length and
diameter by a components exhibit increasing returns to scale, which
general observations can be made. The cost of all four
over, the values of the sum is greater than one, increasing returns to scale. More-
is less than one, there are decreasing returns to scale, and if
¼
4
6
7
the intercept and regional variables in Eq. (7) are collected
into a single term and rearranged, the cost model can be
rewritten in Cobb-Douglas form1:

\[ C = bL^{a_1}D^{a_2}, \]

where \( \log(b) = a_0 + a_1\text{NE} + a_2\text{SE} + a_3\text{CL} + a_4\text{SW} + a_5\text{W} \)

There are several properties of Cobb-Douglas functions that
are of interest in the context of the cost models. If the sum of \( a_0 \)
and \( a_2 \) is equal to one, the capital cost exhibits constant
returns to scale (i.e., cost is linear with \( L \) and \( D \)). If the sum
is less than one, there are decreasing returns to scale, and if
the sum is greater than one, increasing returns to scale. More-
ever, the values of \( a_0 \) and \( a_2 \) represent the elasticity of cost
with respect to length and diameter, respectively.

Parameter estimates for the materials, labor, miscellaneous
charges, and ROW cost components are given in
Table 1. The generalized regression model given in Eq. (7)
accounts for a large proportion of the variation in the data
set for each of the cost categories, as reflected by all of the
cost component models having an adjusted-\( r^2 \) value greater
than 0.81, with the exception of ROW, which has an
adjusted-\( r^2 \) value of 0.67.

Based on the regression results shown in Table 1, several
general observations can be made. The cost of all four
components exhibit increasing returns to scale, which
means that multiplying both the length and diameter by a constant \( n \) multiplies the materials cost by a factor greater
than \( n \). For example, doubling both pipeline length and
diameter results in a nearly 6-fold (rather than 4-fold)
increase in materials cost. For the materials, labor and
miscellaneous costs, the elasticity of substitution for length is
less than one; thus, a doubling in pipeline length results in
less than a doubling of the cost for these components (often
referred to as economies of scale). However, the elasticity
of substitution for length in the ROW cost is approximately
one, so that doubling the length results in a doubling of ROW
cost (which is reasonable, as the ROW cost per unit of land
should be approximately constant regardless of the pipeline
length). The elasticity of substitution for pipeline diameter is
less than one for labor, miscellaneous, and ROW costs, again
indicating economies of scale; however, for materials cost it
is approximately 1.6, so that doubling the pipeline diameter
results in a 3-fold materials cost increase. Note that this still
reflects an economy of scale in the total cost of materials
since doubling the diameter would quadruple the total mass
of steel needed.

At least one regional variable was found to be statistically
significant in all of the regression model cost categories,
implying that for some regions, the cost of constructing a
pipeline is higher or lower than the average for the Midwest
region. For example, the labor cost regression results (Table 1)
show that the cost multiplier is approximately US$ 600
greater in the Northeast than the Midwest and approximately
US$ 10,000 lower in the Central and Southwest regions. There
is no statistical difference (at the 5% level) between the
Midwest and West or Southeast cost intercepts.

Cost differences between regions could be caused by a
combination of two types of factors: differences between
regions in the average cost of materials, labor, miscellaneous
costs, and land (affecting ROW cost); and, differences in
other geographic factors, such as population density and
terrain. Regional variation in labor and materials cost for
power plant construction have been documented by the
Electric Power Research Institute (EPRI) (Electric Power
Research Institute, 1993). However, because the routings of
pipeline projects are not reported in the data set, it is not
possible to identify how these individual factors contributed
to overall cost of the projects. Thus, there are plausible
circumstances where similar pipeline projects in different
regions could have costs much closer to one another than to
comparable projects within their respective regions (e.g.,
pipelines of similar length and design CO2 mass flow in
heavily populated versus unpopulated areas within the
same state). Zhang et al. (2007) have developed more data
intensive tools to study least-cost routing of specific CO2
pipelines which are complimentary to the use of the current
screening level model.

While operating and maintenance (O&M) costs are not
large in comparison to the annualized capital cost of pipeline
transport, they are nonetheless significant. Bock et al. (2003)
report that the O&M cost of operating a 480 km CO2 pipeline is
between US$ 40,000 and US$ 60,000 per month. On an annual
basis, this amounts to approximately US$ 3250 per kilometer
of pipeline in 2004 dollars.

### Table 1 – Regression coefficients for the pipeline cost model, Eq. (7); with standard errors indicated in parentheses

<table>
<thead>
<tr>
<th>Coefficient estimate</th>
<th>Materials</th>
<th>Labor</th>
<th>ROW</th>
<th>Miscellaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 )</td>
<td>3.112** (0.067)</td>
<td>4.487** (0.109)</td>
<td>3.950** (0.244)</td>
<td>4.390** (0.132)</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>0.075 (0.032)</td>
<td>0.187 (0.048)</td>
<td>0.382** (0.093)</td>
<td>0.369** (0.061)</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>0.074** (0.021)</td>
<td>–</td>
<td>–</td>
<td>0.377** (0.066)</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.382** (0.061)</td>
</tr>
<tr>
<td>( a_4 )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.377** (0.066)</td>
</tr>
<tr>
<td>( a_5 )</td>
<td>0.901** (0.012)</td>
<td>0.820** (0.023)</td>
<td>1.049** (0.048)</td>
<td>0.73** (0.027)</td>
</tr>
<tr>
<td>( a_6 )</td>
<td>1.590** (0.045)</td>
<td>0.940** (0.077)</td>
<td>0.403** (0.167)</td>
<td>0.791** (0.091)</td>
</tr>
</tbody>
</table>

* Significant at the 5% level.

* Significant at the 1% level.

1 In economic theory, a Cobb-Douglas production function has
the form \( f(K,L) = AK^aL^b \), where \( K \) and \( L \) traditionally refer to capital
and labor.
5. Combining performance and cost

To facilitate calculations, the linked pipeline performance and cost models have been programmed as a stand-alone spreadsheet model using Visual Basic in Microsoft Excel. Implementation of all equations has been validated by comparing spreadsheet results to manually calculated results using the same input parameters. The pipeline model has also been implemented in the Integrated Environmental Control Model (IECM), a power plant simulation model developed by Carnegie Mellon University for the U.S. Department of Energy (USDOE) to estimate the performance, emissions, and cost of alternative power generation technologies and emissions control options (Rao and Rubin, 2002; Berkenpas et al., 2004). The new CO2 pipeline transport module allows the IECM to analyze in greater detail the performance and cost of alternative CO2 capture and sequestration technologies in complex plant designs involving multipollutant emission controls.

The key results reported by the newly developed pipeline model include the total capital cost, annual O&M cost, total levelized cost, and the levelized cost per metric tonnes of CO2 transported (all in constant 2004 US dollars). The capital cost can be subject to capital cost escalation factors applied to individual categories of the capital cost (i.e., materials, labor, miscellaneous, and ROW). These escalation factors can be used to account for anticipated changes in capital cost components (e.g., in the cost of steel) or other project-specific factors that might affect capital costs relative to the regional averages discussed earlier (e.g., river crossings). Capital costs are annualized using a levelized fixed charge factor calculated for a user-specified discount rate and project life (Berkenpas et al., 2004). The cost per tonne CO2 transported reflects the amount of CO2 transported, which is the product of the design mass flow rate and the pipeline capacity factor.

6. Case study results

Illustrative results from the pipeline model were developed using parameters representative of a typical coal-fired power plant in the Midwest region of the United States (Table 2). Several parameter values (e.g., capital recovery factor) are default values from the IECM software. Table 2 includes a nominal CO2 mass flow rate and pipeline length, but these two parameters are varied parametrically in the case study results presented here.

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Deterministic value</th>
<th>Uncertainty distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design mass flow (Mt/year)</td>
<td>5</td>
<td>Variable*</td>
</tr>
<tr>
<td>Pipeline length (km)</td>
<td>100</td>
<td>Variable*</td>
</tr>
<tr>
<td>Pipeline capacity factor (%)</td>
<td>100</td>
<td>Uniform (50, 100)</td>
</tr>
<tr>
<td>Ground temperature (°C)</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Inlet pressure (MPa)</td>
<td>13.79</td>
<td>Uniform (12, 15)</td>
</tr>
<tr>
<td>Minimum outlet pressure (MPa)</td>
<td>10.3</td>
<td></td>
</tr>
<tr>
<td>Pipe roughness (mm)</td>
<td>0.0457</td>
<td></td>
</tr>
<tr>
<td>Economic and financial parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project region</td>
<td>Midwest</td>
<td>Uniform (10, 20)</td>
</tr>
<tr>
<td>Capital recovery factor (%)</td>
<td>15b</td>
<td>Uniform (2150, 4350)</td>
</tr>
<tr>
<td>Annual O&amp;M cost (US$/km/year)</td>
<td>3250</td>
<td>Uniform (0.75, 1.25)</td>
</tr>
<tr>
<td>Escalation factor for materials cost</td>
<td>1</td>
<td>Uniform (0.75, 1.25)</td>
</tr>
<tr>
<td>Escalation factor for labor cost</td>
<td>1</td>
<td>Uniform (0.75, 1.25)</td>
</tr>
<tr>
<td>Escalation factor for ROW cost</td>
<td>1</td>
<td>Uniform (0.75, 1.25)</td>
</tr>
<tr>
<td>Escalation factor for miscellaneous cost</td>
<td>1</td>
<td>Uniform (0.75, 1.25)</td>
</tr>
</tbody>
</table>

* This parameter is modeled as a series of discrete values.

b Corresponds to a 30-year plant lifetime with a 14.8% real interest rate (or, a 20-year life with 13.9% interest rate).

<table>
<thead>
<tr>
<th>Table 3 – The levelized cost of pipeline transport in the Midwest and regional differences relative to the Midwest, based on assumptions in Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport cost (US$/tonne CO2)</td>
</tr>
<tr>
<td>--------------------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Materials</td>
</tr>
<tr>
<td>Labor</td>
</tr>
<tr>
<td>ROW</td>
</tr>
<tr>
<td>Miscellaneous</td>
</tr>
<tr>
<td>O&amp;M</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Bracketed values are negative (all costs in constant 2004 US dollars).
For the case study CO₂ pipeline, the total levelized cost is estimated to be US$ 1.16 per tonne of CO₂ transported. Table 3 shows the regional differences in CO₂ transport cost relative to the Midwest region for a pipeline with the same parameters as in Table 2. In general, the model shows that the cost is greatest in the Northeast, followed by (in descending order) the Southeast, Midwest, West, Southwest, and Central U.S. This trend applies to all pipeline lengths and design mass flows. Overall, the cost category that accounts for the largest regional difference is the labor cost, which is lowest in the Southwest and highest in the Northeast.

Fig. 5 shows results from the model as a function of pipeline distance for a project in the Midwest for four different design mass flow rates. In this example the pipeline capacity factor is assumed to be 100%, so the annual mass transported equals the design capacity of the pipeline. Fig. 5 shows that the levelized transport cost increases with distance and decreases with increasing design capacity for a fixed distance. For a typical 500 MW power plant (emissions of approximately 2–3 million tonnes per year), transport cost could range from US$ 0.15 per tonne for a 10 km pipeline to US$ 4.06 per tonne for a 200 km pipeline based on a 100% capacity factor. For an annual capacity factor of 75% (typical of existing coal-fired power plants), the levelized cost per tonne would increase to between US$ 0.20 per tonne for the 10 km pipeline to US$ 5.41 per tonne for 200 km pipeline. Fig. 5 also illustrates the differences in levelized cost between the same pipeline constructed in the Northeast and Central regions. For all pipeline distances and all pipeline design capacities, the transport cost is lowest in the Central region and highest in the Northeast region.

7. Comparison with other studies

A number of recent studies and reports have estimated the cost of onshore CO₂ pipelines, including studies by IEAGHG (Woodhill Engineering Consultants, 2002), MIT (Bock et al., 2003), and Hendriks et al. (2003). To the best of our knowledge, however, there are no publicly available CO₂ pipeline cost models that have been published in peer-reviewed journals. Results from these and other recent studies were compared in the IPCC Special Report on Carbon Dioxide Capture and Storage (Doctor et al., 2005). Levelized costs generated by the current pipeline model are compared with the range of results presented by the IPCC for onshore pipelines, represented by the shaded area in Fig. 6. Parameter values for our model are listed in Table 2, where a fixed distance of 250 km was used for pipeline length, and mass flow varied, consistent with the IPCC assumptions. Costs estimated by the pipeline model agree well with the IPCC results, although that report does not specify assumptions beyond the pipeline length and mass flow rate. Thus, parameter values different from those listed in Table 2 could generate transport costs lower or higher than the IPCC range.

8. Probabilistic results

To assess the sensitivity of the model to changes in multiple design and financial parameters, uniform distributions were assigned to several parameters of interest and a series of Monte Carlo trials were used to calculate the pipeline transport cost. The uniform distribution was selected to represent uncertainty or variability because there is no prior information that would suggest choosing a more complex distribution (such as a triangular or lognormal distribution). The design parameters of interest are the ground temperature, and pipeline inlet pressure, while financial parameters include pipeline capacity factor, capital recovery factor, and annual pipeline O&M cost. Values of the input parameters for the probabilistic analysis are also shown in Table 2.
For this analysis, 1000 trials were conducted. From these trials a cumulative distribution function (CDF) for transport cost was generated, shown in Fig. 7. The CDF shows that for a Midwest pipeline project transporting 5 million tonnes of CO₂ annually over 100 km, a 90% probability interval (which reflects the selection of input parameters) yields levelized costs between approximately US$ 1.03 and US$ 2.63 per tonne of CO₂ transported. The minimum and maximum cost predicted by the model are US$ 0.75 and US$ 3.56 per tonne of CO₂ transported; however, these values are very sensitive to the number of Monte Carlo simulations performed. A less sensitive measure is the median cost of transport, which is US$ 1.65 per tonne under these conditions.

Using the cost models for different regions changes the results of the sensitivity analysis, also shown in Fig. 7. Thus, a project in the Central US region will have costs less than a project in the Midwest or Northeast for all combinations of input parameters. The median cost of the case study project in the Central US is US$ 1.09 per tonne CO₂, with a 90% confidence interval between US$ 0.70 and US$ 1.69 per tonne. In the Northeast, the project cost could approach that of the Midwest for some combinations of input parameters. The median cost of this project in the Northeast is US$ 1.90 per tonne CO₂, with a 90% confidence interval between US$ 1.16 and US$ 3.14 per tonne.

Results of the Monte Carlo trials can also be used to assess the sensitivity of transport cost to the uncertain model parameters. The measure used to assess the sensitivity is the Spearman rank-order correlation (rₛ) (Morgan et al., 1990). Similar to the commonly used Pearson product–moment correlation (i.e., r-value), which measures strength of a linear relationship between variables, rank-order correlation is a measure of direction and association between the statistical rank of variables. The value of the rank order correlation coefficient between transport cost and each uncertain model parameter is shown in Fig. 8. The dashed vertical lines to the left and right of the axis in Fig. 8 indicate the 5% significance level (rₛ = ±0.07); rank-order correlation coefficients smaller than this value are not statistically significant at the 5% level. Fig. 8 shows the strongest correlation is between transport cost and pipeline capacity factor (rₛ = −0.66), followed by capital recovery factor (rₛ = 0.63). Following these, significant rank-order correlation coefficients (by decreasing magnitude) are the labor escalation factor, inlet pressure, materials escalation factor, and ROW escalation factor. This implies that the pipeline capacity factor and capital recovery factor are far stronger determinants of pipeline transport cost than any of the escalation factors. For example, to double the levelized cost of transport for the illustrative CO₂ pipeline (parameters presented in Table 2) the capital cost escalation factor for pipeline materials would have to be increased between 400 and 800%, depending on the project region. By contrast, only a 50% reduction in the pipeline capacity factor is required to double the levelized cost.

9. Conclusions

The model of CO₂ transport developed in this paper builds on past work in this area by linking the design of CO₂ pipelines with the cost of construction and operation to arrive at the total cost of CO₂ transport for six major regions of the United States. For the illustrative example presented here (i.e., 5 million tonnes of CO₂ transported annually over 100 km in the Midwest), the estimated cost of CO₂ transport was US$ 1.16 per tonne of CO₂; however, this cost could vary by over 30% for other US regions of construction. CO₂ transport costs can vary more significantly with pipeline length and design capacity. For example, for a typical 500 MW power plant in the Midwest the model estimates costs that ranged from US$ 0.15 per tonne for a 10 km pipeline to US$ 4.06 per tonne for a 200 km pipeline. Cost of construction is generally greatest in the Northeast and
least in the Central region of the US. An illustrative probabilistic analysis showed how the model can yield a range of transport costs for a particular project reflecting the uncertainty or variability of project parameters. The probabilistic analysis further showed that the most important determinants of the pipeline cost for a specific project were likely the pipeline capacity factor and the capital recovery factor.

Using this model in combination with performance and cost models of CO₂ capture and storage technologies can allow the overall cost of an integrated project to be estimated with greater accuracy than afforded by with generic rule-of-thumb estimates for transport costs, as often found in the literature. The Integrated Environmental Control Model (IECM) developed at Carnegie Mellon (Berkenpas et al., 2004) is an example of a tool with that capability. The CO₂ transport model developed here also is suitable for use in addressing larger questions on the optimal policies that might encourage infrastructure development to support carbon capture and storage.

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REFERENCES


Smeyers, R., Odenberger, M., Johnson, I., Stromberg, I., 2004. Transportation systems for CO₂-application to carbon
Thambimuthu, K., Soltanieh, M., Abanades, J.C., Allam, R.,
Bolland, O., Davison, J., Feron, P., Goede, F., Herrera, A., Iijima,
Coninck, H., Loos, M., Meyer, L. (Eds.), IPCC Special Report on
Carbon Dioxide Capture and Storage. Cambridge University
Press, Cambridge, UK.
True, W.R., 1995. U.S. interstate pipelines ran more efficiently in
J. 94 (48), 39.
True, W.R., 1997. Construction plans jump; operations skid in
1996. Oil Gas J. 95 (31), 37.
True, W.R., 1999. U.S. pipelines experience another tight year,
reflect merger frenzy. Oil Gas J. 97 (34), 13.
98 (36), 68–86.
True, W.R., 2000b. More construction, higher costs in store for
US pipelines. Oil Gas J. 98 (36), 68–70.
companies, more gas capacity planned. Oil Gas J. 100 (38), 52.
True, W.R., 2003a. US pipeline companies solidly profitable in
2002, scale back construction plans. Oil Gas J. 101 (34), 60–90.
101 (34), 60–90.
companies experience flat 2003, continue mergers. Oil Gas J.
102 (32), 52.
6. IEA Greenhouse Gas R&D Programme, Stoke Orchard, UK.
Zhang, H., Li, W., Herzog, H., 2007. MIT CO2 Pipeline Transport
and Cost Model. Massachusetts Institute of Technology:
Carbon Capture and Sequestration Technologies Program,
Boston, Massachusetts.
Optimization of pipeline transport for CO2 sequestration.
Zigrang, D.J., Sylvester, N.D., 1982. Explicit approximations to
the solution of colebrook friction factor equation. AIChE J.
28 (3), 514–515.