Economic modeling of carbon dioxide integrated pipeline network for enhanced oil recovery and geologic sequestration in the Texas Gulf Coast region

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Abstract

Naturally occurring CO_2 is transported via pipelines to oil fields in West Texas to enhance production. A similar pipeline system is proposed for the Gulf Coast region of Texas. The CO_2 would come from anthropogenic sources. Using GIS data, oil fields and CO_2 sources are selected and a pipeline route is designed, taking into consideration rights of way and environmental sensitivities. We modified several pipeline cost models from the literature to capture recent construction cost escalations. Our resulting cost estimates agree with mid-to-high range cost quotes for pipelines reported to the Federal Energy Regulatory Commission by the companies.

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1. Introduction

CO_2 transportation by pipeline has been taking place since the 1980s in West Texas for enhanced oil recovery (EOR). Three large pipelines, of inner diameters ranging from 20 to 30 inches and covering distances ranging from 295-803 km carry CO_2 (97-98% pure) from natural sources in different locations outside Texas to Denver City in West Texas. From this hub CO_2 is distributed through an outlet network to the oil fields. The CO_2 is transported at pressures between 7.5 and 18 MPa to keep it at supercritical phase required for dense-phase flow.

1.1. CO_2 Supply network for Gulf Coast region of Texas

A similar multi-source CO_2 pipeline infrastructure is proposed for the Gulf Coast region of Texas for EOR but also for geologic sequestration. Unlike the West Texas network, the CO_2 would come from largely manmade sources such as fossil fuel based power plants (Figure 1). This multi source "n-source to m-sink" pipeline network model allows flexibility of operations for both the CO_2 capture plants and the oil fields. For instance, CO_2 supply would not suffer should a source go offline for general maintenance or decide to operate below its regular capacity for commercial reasons. Other sources could pick up by increasing their capacity factors. Secondly, since a source is not tied to any specific oil field, the latter would not suffer when the source is shut down, and vice versa. The pipeline network can expand by adding new supply lines from future plants and can also be made to serve new oil fields by additional pipeline outlets.

The Gulf Coast Carbon Center (GCCC) of the Bureau of Economic Geology (BEG) has secured a database of all oil and gas fields and all stationary sources of CO_2 in Texas and has established an inventory of all CO_2-EOR candidate oil fields. Indications suggest that about 1.5 billion stock barrels of oil can be recovered from existing candidate fields in the Texas Gulf Coast with a flooding of about 200 million tonnes of CO_2. Over half a billion tonnes of carbon dioxide can also be sequestered after the 'economic oil' has been recovered. In this context, CO_2, which is a waste gaseous stream and a contributor to climate change would be used to create an economic activity in the Gulf Coast region[2]
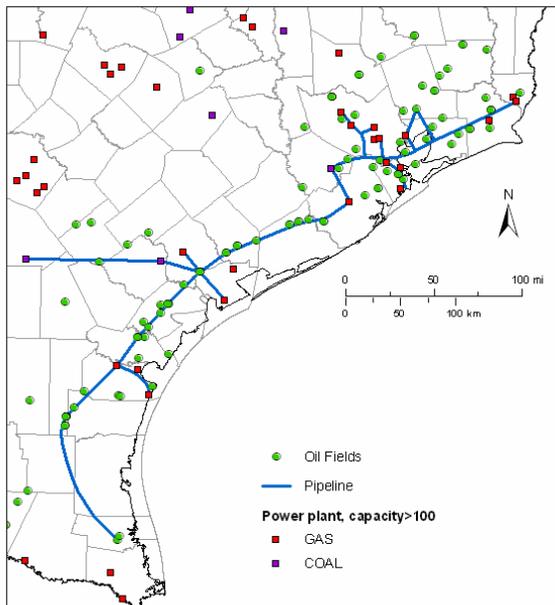
Texas and also would be sequestered. This paper estimates the total capital cost for constructing such a pipeline network infrastructure. It is limited to the Texas Gulf Coast (referred to as Railroad Commission Region Six) and only power plants are being considered as sources.

Figure 1 – Proposed CO₂ pipeline network

2. Methodology

Using a GCCC/BEG database of CO_2 sources (mostly power plants) and oil fields that are EOR capable, we focused on the Gulf Coast region to design the pipeline network. There are a large number of sources and fields in this region as well as existing rights of way for various pipelines. In general the region is quite familiar with oil & gas activity. In order to calculate the cost of the pipeline, we surveyed the literature on CO_2 pipeline economics. We compared several models in terms of their cost estimates and their consistency with recent construction costs of pipelines as reported to the Federal Energy Regulatory Commission (FERC). At the end, we

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[2] Texas Railroad Commission is the regulator of pipelines in Texas.

used modified cost estimates based on a cost escalation factor we calculated. Detailed steps of our methodology follow.

Though oil refinery flue gas equally contains more CO_2, we decided to tackle emissions from power plants for the following reasons; total power plant emissions is the most significant; it accounts for 84% of CO_2 emissions compiled. Secondly, 26–28 refineries are in the whole of Texas; but over 40 large power plant (300 MW and above) are in the Gulf Coast Region alone.

- First, ,we used the GIS database to identify power plants and oil fields in Railroad Commission Region Six.
- Next, we shortlisted 31 large oil fields, which, in the estimation of BEG, are best candidates for EOR and eventually for sequestration and accounts for almost 60% of the recoverable oil via EOR. Total demand for CO_2 is estimated at 806 million tonnes if only the main oil fields are considered but goes up to about 831 million tonnes if surrounding catchments are included.
- We then superimposed the GIS map of the power plants and that of the 31 major oil fields to match the power plants with the nearest oil fields. The total CO_2 requirement of the fields is between 40 and 42 million tonnes per year if 20 year economic life of operation is considered. As a result, six large gas-fired plants (460-1,422 MW) and five coal fired plants (184-892 MW) were selected from existing 45 gas and 17 coal fired plants.
- We design the pipeline network based upon the CO_2 mass flow rates from the selected power plants to the oil fields.
- Then, we estimated the capital cost of this pipeline network. Cost estimation using available models, however, seems to under-estimate the total cost when compared to recent project announcements by the industry [1].
- The next step therefore was to develop an escalation factor using regression analysis from results of the various pipeline cost models and comparing them to the estimated costs announced by the industry.
- Environmental Impact assessment and for that matter risk analysis has not been undertaken yet.

3. Pipeline network design

3.1. Source selection and the Right of Way (ROW)

We used the following criteria to screen the power plants:
- Land availability for the capture equipment.
- Long operational life remaining, since retrofit of existing plants is also an option.
- Ability to handle additional cooling water and wastewater discharge.
- Flexibility to adapt gas-fired plant for dual fuel firing capability in future (here coal gasification).
- Coal plants' ability to accommodate expansion or additional scrubbers to handle the additional NO_X and SO_X emissions.
- Ability to meet existing environmental permits with the additional equipment and the local emissions.
- ROW for new pipelines

Although the concentration of CO_2 emissions are lower for gas-fired plants, they are included because gas generates about half of electricity in Texas and is also preferred around the country as it burns relatively cleaner than coal. Existing gas plants that used to operate below 50% capacity factors (CF) in 2006 are now operating at higher CF and will likely continue to do so in the future. Investors in these relatively new plants would also like to generate and sell more power to recoup their investments. High CF, however, implies higher and significant GHG emissions. As such, gas-fired plants would be compelled to undertake mitigation measures as well.

The largest gas plant selected is 1,422 MW located in Harris County. The six gas fired plants will provide a total emission of 27 million tonnes annually. The largest coal plant selected is 890 MW located in Bexar County. There is also the option to select a 3,969 MW plant located in Fort Bend County but its relatively large size means there might not be enough land for the capture plant based on the information available at the time of writing. In general, coal plants would require larger land area for capture technology than gas plants. The maximum CO_2 that can be supplied by the power plants at 95% capture is 52 tonnes per annum (2.7 billion cubic feet per day). This is greater than the requirements for EOR but necessary, because losses occur at the booster stations and power plants may not all operate at their maximum capacity factors at all times.
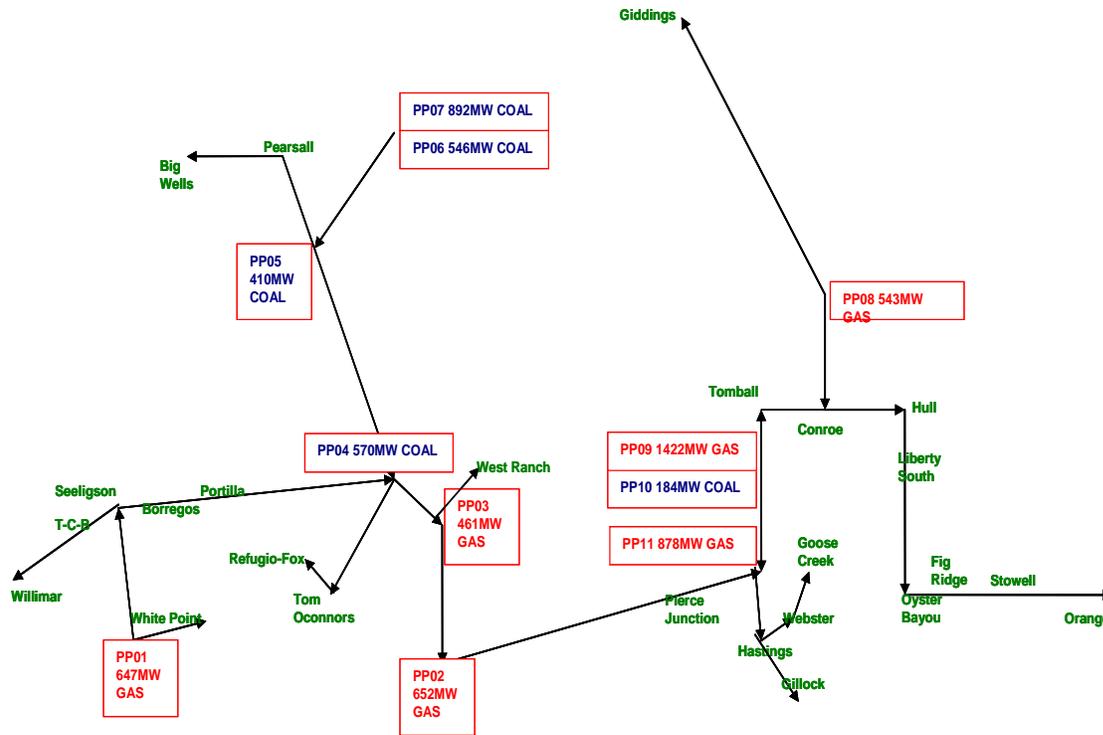
Figure 2 – Power plants and oil fields connected by the CO₂ pipeline network

The pipeline network is onshore and consists of various lengths of pipelines in various diameters, ranging from eight inches to 52 inches. The total length of pipe that will be laid is about 1,600 km. To keep construction cost to a minimum it is important to avoid obstacles along the right of way, which also helps with project acceptance and

permitting. A pipeline made to go through a highly populated area, a wetland or a waterway can increase the ROW cost by 10-15 times if it is ever going to be permitted. Passing through high elevation terrains and crossing highways

and the like would also increase the cost. However, pipelines following existing rights of way such as natural gas or oil pipelines, underground power cables or water pipelines will help keep cost low as well as avoid local opposition.

The selected 31 fields for the EOR with their estimated oil potential include: Conroe (218 million stack barrels), Hastings (190 million stack barrels), Webster (173 million stack barrels), Tom O'Connor (155 million stack barrels), Giddings (68 million stack barrels) and Refugio-Fox (14 million stack barrels).[3] Figure 2 is the resulting **path** for the pipeline network proposed for the Gulf Coast region of Texas, avoiding the discussed barriers.

3.2. Hydraulic Parameters

For a fluid to be suitable for transportation, the *temperature* (assumed to be the same as the surroundings) and the *density of the fluid* are the two main properties to be considered. Transporting a high density fluid facilitates efficient transportation because a large mass per unit volume can be shipped. To maximize pipeline throughput and minimize cost of transportation, CO_2 is shipped in supercritical/dense state, which also ensures one phase flow which is relatively easier to handle compared to multiphase flow. Operating temperatures of CO_2 pipelines are generally dictated by the temperature of the surrounding soil. In the Gulf Coast region of Texas, average ambient air

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[3] Potential for Hastings if catchments are included is about 296 million stack barrels and that of Tom O'Connor if catchments are included is about 184 million stack barrels.

temperatures range between 10-20 degrees Celsius (°C) in winter and 24-29°C during summer.[4] Soil temperature would depend upon the thermal conductivity of the soil. The pipeline internal diameters based on CO_2 supercritical/dense flow rate are estimated using a model proposed by McCoy [2]. The McCoy model assumes that the fluid is pure CO_2. The McCoy model further assumes an isothermal flow although, in practice, there is a significant increase in temperature after compression which affects fluid behaviour and horsepower requirement. For this reason, the pipeline diameters are adjusted upwards to cover the extra expansion and also to take into account common line-pipe sizes. The next step therefore, is to estimate the compression and to find out the pressure drops, along the pipeline as to know where to install compressors or what initial compression pressures to use in order to maintain supercritical/dense flow of the CO_2 from the initial source to final destination. For instance pressure drop in a typical 20-inch pipeline is about 30 kPa per km assuming a constant temperature. Critical point of CO_2 phase occurs at 31.4°C and 7.38 MPa. For instance, for a 121-km, 10-inch pipeline, initial pressure of 7.38 MPa will drop to 6 MPa at 100 km. To maintain a supercritical phase, the initial compression pressure should be between 13-14 MPa. We used typical values from other authors to produce a relationship, which can be represented by the following formula: (pressure drop in kPa) = 571.48(pipe diameter in inches)$^{-1.0076}$. Using this formula, one can estimate pressure drop for other pipeline sizes (Figure 3).

Line-pipes with ASME-ANSI Class 900# and 1500# ratings are envisaged. Line-pipe with ASME-ANSI Class 900# flanges has a maximum allowable operating pressure of 15.3 MPa at 31.4°C (88.5°F). Higher pressures require ASME-ANSI Class 1500# flanges (see Mohitpour et al. [3]).
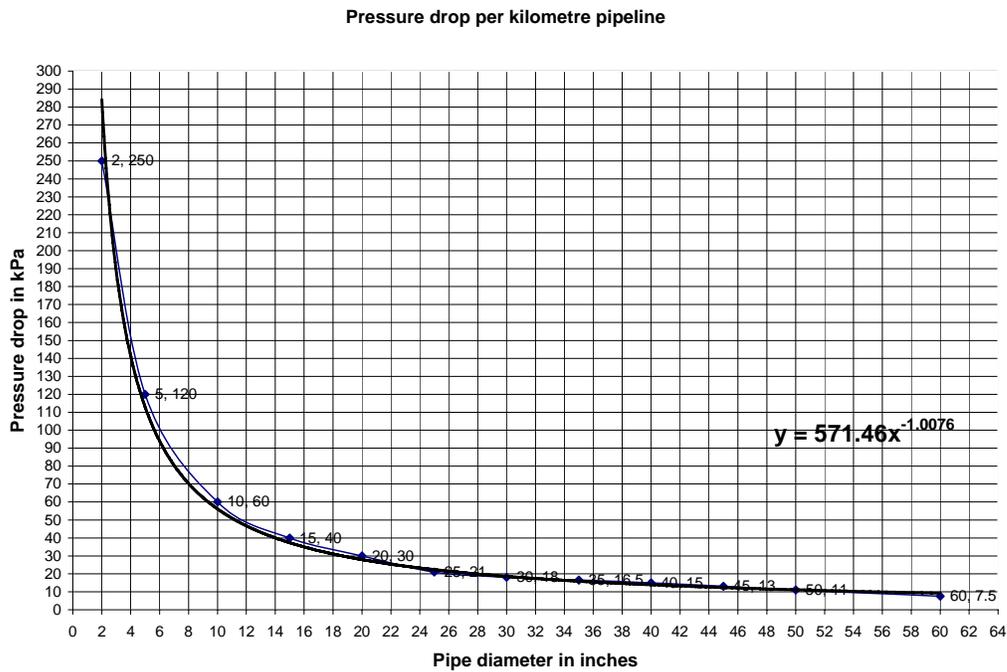
Pressure drop per kilometre pipeline

Figure 3. CO2 pipeline pressure drop chart

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[4] Temperature rarely falls below zero in winter.

The integrated pipeline network linking the 11 power stations to 31 oil fields would cover about 1,600-1,824 km with CO_2 flow rate of 41-55 million tonnes per year based on 20-25 year economic life and with pipeline diameters
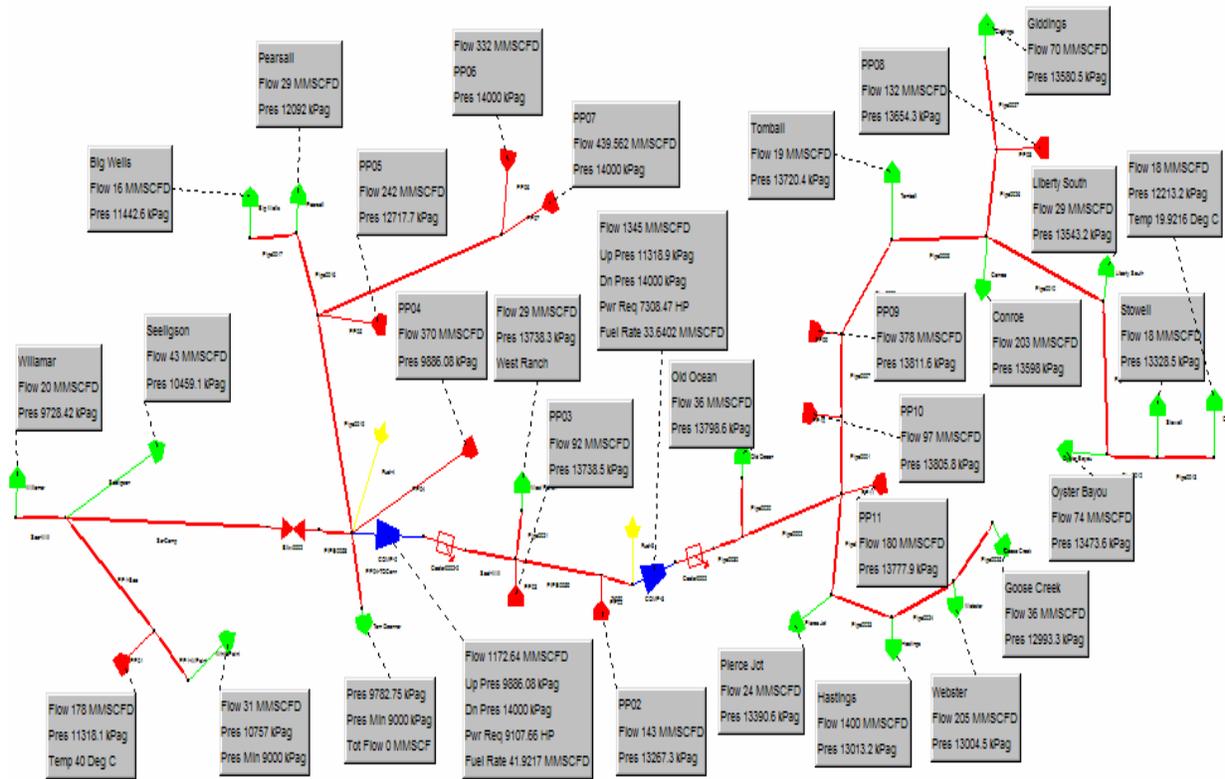

Figure 4 – CO_2 flow from power plants to fields and compression pressures

ranging from 8-40 inches (203-1016 millimetres). Two booster stations would be required for the network (Figure 4). The location of the booster stations accomplishes two things: the suction control pressure ensures that the supercritical conditions are maintained while the discharge control pressure boosts the system pressure for further downstream transportation.[5]

4. Cost of the pipeline network

Total installed cost of a pipeline is made up of the following four key cost categories; Material, Labor, Right-of-Way (ROW) and miscellaneous expenses. Detailed construction data for actual CO_2 pipeline costs are sparse and largely outdated. Not many CO_2 pipeline projects of this scale have been constructed since the 1990s. Different pipeline cost models were therefore consulted to compute the cost of our pipeline network. These models are described in following studies: MIT [4], Ecofys [5], Ogden [6], Parker [7], IEA [8], McCollum & Ogden [9] and McCoy [10]. McCoy, MIT, IEA and Parker used historical natural gas pipeline costs to develop the cost equations for their cost models. Except for the McCoy and Parker models, all the models provide cost in **$ per inch per km.** The various models are able to predict pipeline capital cost of the past to some extent but are challenged when used for CO_2 pipeline projects announced by the industry since 2006. This is after ROW conditions like terrain and the dollar-year have been standardized for all the equations.

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[5] Software is Pipeline Studio Software 3.0 developed by Energy Solutions International (www.pipeline-design.com; www.energy-solutions.com).

4.1. Accounting for cost escalation

Because the MIT, McCoy, IEA GHG2005/3 and the Parker models all used historical cost data for natural gas pipeline construction in the United States, a possible unified common factor from their model equations was sought. Using regression analysis, we found and defined an escalation factor λ for the total CO_2 pipeline capital cost as

$$\lambda = \frac{3\eta\,(\gamma\alpha\beta\,)}{\gamma + \alpha + \beta}$$

Where η is Labor escalation cost factor, i.e.

$$\eta = \frac{\text{average cost of labor in current year}}{\text{average cost of labor in base year}} \qquad \eta > 0$$

For instance, if labor cost was \$25,000 per inch per km in 2006, but in 2007 it increased to \$50,000 per inch per km, η is 2. If it was the same as in 2006, $\eta = 1$.

γ is Material escalation cost factor, α is Miscellaneous escalation cost factor and β is ROW escalation cost factor; they are all calculated similar to η and γ, α, $\beta > 0$

For year n, λ_n becomes:

$$\lambda_n = \frac{3\eta_n(\gamma_n\alpha_n\beta_n)}{\gamma_n + \alpha_n + \beta_n}$$

By inserting λ_n into the MIT and the IEA GHG2005/3 models, the resulting modified models are as follows:

The **modified MIT model equation**[6] is:

$$(\frac{3\eta_n\gamma_n\alpha_n\beta_n}{\gamma_n + \alpha_n + \beta_n}) * \$20{,}989/\text{in}/\text{km} = (\frac{\eta_n\gamma_n\alpha_n\beta_n}{\gamma_n + \alpha_n + \beta_n}) * \$62{,}967/\text{in}/\text{km}$$

The **modified IEA GHG2005/3 model equation**[7] is:

$$(\frac{3\eta_n\gamma_n\alpha_n\beta_n}{\gamma_n + \alpha_n + \beta_n}) * \$25{,}889/\text{in}/\text{km} = (\frac{\eta_n\gamma_n\alpha_n\beta_n}{\gamma_n + \alpha_n + \beta_n}) * \$77{,}667/\text{in}/\text{km}$$

McCoy and Parker models go beyond by providing equations for the four major pipeline cost categories of *materials*, *labor*, *ROW* and *miscellaneous* costs: One has the option to just plug categorical escalation factors of η, γ, α and β in the McCoy or Parker set of equations to obtain the escalated costs. We therefore used regression analysis to test the modified MIT and the IEA models with those of the Parker and McCoy models and the correlation coefficients average 91%. The MIT or the IEA GHG 2005/3 model modified with the escalation factor λ thus can provide quick and robust estimates. The IEA GHG2005/3 model provides the highest and the MIT model provides the lowest cost estimates. McCoy and Parker model values fall within the output values of the MIT and the IEA GHG2005/3 model equations. The models' results and announced cost estimates differ; in our estimation, to be able to predict the total CO_2 pipeline capital costs announced by the industry since 2006, the **cost per inch per km** given by any model should be at least **\$50,000**. The discrepancy is mainly due to significant increase in costs experienced in recent years.

We also considered a chemical difference between CO_2 and natural gas; CO_2 is an acidic precursor compared with natural gas and for that matter corrosive, even though weak. The material of a CO_2 pipeline is thus more reinforced, which means additional cost, about 10% over a natural gas pipeline of similar size and length[8]. This

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[6] MIT concludes that on the average, the construction cost for a CO_2 pipeline would be \$20,989/in/km.

[7] IEA GHG2005/3 concludes that on the average, the construction of a CO_2 pipeline would cost \$25,889/in/km.

[8] Industry information from Pipeline Design Solutions, www.pipeline-design.com. Contact Ben Asante, Ph.D, P.Eng., (basante@pipeline-design.com).

additional cost has also been factored into estimating the capital cost of the pipeline by multiplying the costs by 10% (i.e. 1.10) to establish the final lower and upper cost boundaries. Overall, we estimate that the total capital cost of the CO_2 pipeline network in the Texas Gulf Coast is in the range of \$2.4-3.4 billion. The corresponding average **cost per km** would be in the range of \$1.5-2.1 million.

5. Conclusions

An onshore pipeline network to transport anthropogenic CO_2 for EOR and eventually for geologic sequestration is proposed for the Gulf Coast region of Texas. This pipeline infrastructure is a multi-source, multi-sink model similar to one that has operated in West Texas for almost three decades. This design allows flexibility of operations for both the CO_2 sources and the oil fields. Since a source is not tied to any specific oil field; the latter would not suffer when the source is shut down, or vice versa. Known CO_2 pipeline cost models were reviewed to evaluate their suitability to our pipeline network. The models were under-estimating the construction costs when compared with announced costs estimates of new projects. Accordingly, cost escalation factors were introduced to selected models to account for cost escalations. Using the models modified as such, we estimated the cost of the proposed pipeline network to be between \$2.4 and \$3.4 billion. Whether such an investment would be warranted would naturally depend on other factors such as cost of capture, price of carbon, additional oil production due to CO_2-EOR, the price of oil but also public acceptance. The next phase of our work would focus on these aspects of CO_2-EOR economics. No environmental impact assessment has been done yet.

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