Developing a carbon management strategy is a formidable task for nations as well as individual companies. It is often difficult to understand what options are available, let alone determine which may be optimal. In response to the need for a better understanding of complex carbon management options, Battelle has developed a state-of-the-art Geographic Information System (GIS) model with economic screening capability focused on carbon capture and geologic sequestration opportunities in the United States.

This paper describes the development of this GIS-based economic screening model and demonstrates its use for carbon management analysis.

Background

As the world begins to come to terms with the risks posed by the threat of climate change and the magnitude of the problem becomes clearer, a set of solutions are being examined to mitigate such risks. Carbon capture and sequestration is one weapon in the arsenal against this threat. In fact, research indicates that advanced carbon capture and sequestration technologies may be a vital component of a plan to transition from today’s energy technology base (designed around the free venting of carbon dioxide (CO₂) to the atmosphere), to the set of advanced low- and non-emitting energy technologies needed to stabilize atmospheric CO₂ concentrations in the future (Dooley et al, 1999). These advanced carbon capture and sequestration technologies also appear suitable for helping achieve near term emission reductions and appear capable of doing so at a cost which is comparable to other alternatives (Dooley et al, 2000).

However, there is still much to be resolved regarding many aspects of carbon capture and sequestration prior to wide scale deployment. Battelle, responding to the need for greater clarity of the existing knowledge base and options impacting carbon management decisions, has
developed a state-of-the-art carbon management geographic information system – the Battelle CO₂-GIS. The system contains information on all fossil-fired generation capacity in the United States and Canada with a rated capacity of at least 100 MW. There are also data on other CO₂ sources (i.e., natural CO₂ domes, natural gas processing plants, etc.) and associated pipelines currently serving enhanced oil recovery (EOR) projects. Data on current and prospective CO₂ EOR projects include location, operator, reservoir and oil characteristics, production, and CO₂ source. The system also contains information on priority deep saline aquifers and deep coal basins with potential for sequestering CO₂ while producing enhanced coalbed methane (ECBM). Additional details of the system’s structure, datasets, and applications have recently been published (Dahowski et al, 2001).

The unique power of a GIS is in its ability to perform spatial analysis and to visually communicate relationships amongst various features. The CO₂-GIS allows users to examine relationships between sources of CO₂ emissions (e.g., fossil-fired power plants) and potential geologic sequestration sites. Key information about the power plants, such as location, type, age, ownership, and presence of environmental control systems can be used along with the emissions data and proximity to potential disposal sites to help develop a strategy for understanding aggregate emissions and addressing potential carbon liability. This can be performed at the individual plant, state, company, and national levels.

**Objective**

The objective of our recent research was to further enhance the utility of the CO₂-GIS by providing additional decision support capability. As a result, a customized economic screening mechanism has been incorporated into the system with the purpose of facilitating prioritization of available geologic sequestration options. The integrated screening tool is automated and easy to use within the existing system. It allows the levelized costs of CO₂ capture, transport, and disposal to be determined for each combination of plant and prospective disposal site. In addition, the value of oil and methane produced from EOR and ECBM processes, along with a value for carbon credits, can be included in the analysis.

The cost data were developed using best available current information and can be easily updated as more knowledge and project experience is gained. Given the current paucity of real world experience with carbon capture and sequestration, we don’t view the results generated by this economic screening tool as a precise measure of actual expected costs; instead, they provide a high-level indication of which option may be most viable for each plant and which plants may be the best targets for capture and sequestration projects. The purpose was not to develop a detailed cost estimator, and it is understood that ultimate costs will vary based on a variety of factors beyond the realm of this tool (e.g., see Gupta et al, 2001 as an example of the detailed engineering needed for a CO₂ capture and sequestration project). Rather, it is intended that the results provide a comparative indication of the economic viability of CO₂ capture and
sequestration for each available source and sink. This allows users to make informed decisions regarding the deployment of carbon capture and sequestration systems to reduce carbon dioxide emissions and stabilize atmospheric concentration.

**Approach**

The cost of sequestering CO\(_2\) from existing power plants can be broken into three general components: capture, transportation, and disposal. Of course, there are many sub-components that ultimately affect the real cost of implementing such a complex project. However, as this is designed to be a high-level screening tool that provides relative costs rankings as opposed to absolute estimates, these were the primary costs considered, with capture being the dominant of the three.

The automated screening component of the CO\(_2\)-GIS calculates the distance from a generating station to each potential sequestration site within a user-specified radius. It then uses the unique characteristics of the particular plant and site to calculate costs which include such items as initial capital costs, annual energy costs, periodic operations and maintenance (O&M), etc. Individual cost components are calculated using the equations that follow and are then summed to return the total levelized cost ($/ton CO\(_2\)) for capture, transport, and sequestration. The variables and coefficients used are specific to each generating unit and sequestration method, as described below. The total cost is determined as follows:

\[
\text{Total Cost} = \text{Capture Cost} + \text{Transport Cost} + \text{Disposal Cost} - \text{Credit}
\]

In addition to the three main cost components, a credit factor has also been included in the algorithm. The purpose of this is to provide the flexibility to model possible future carbon credits or the cash flows that may result from capture and sequestration. Currently, for EOR and ECBM injection, this value is used to represent the revenue stream resulting from the injected CO\(_2\). For each volume of CO\(_2\) that is injected into an oil or coalbed methane formation, an incremental amount of oil or gas is produced (determined by the net utilization factor or adsorption ratio for the formation). Hence, the CO\(_2\) produces a commodity at a rate tied to its injection whose value can be viewed as a credit to help offset the costs associated with capture, transport, and disposal. An alternate approach would be to use the credit value to represent the current or expected market value for CO\(_2\) (currently about $0.65/mcf in the Permian Basin of West Texas), which would also help to offset some of the costs.

**Capture**

The CO\(_2\)-GIS is currently focused primarily on reducing emissions from existing power generation assets. The cost and performance of CO\(_2\) capture from existing power stations was modeled after the capture technology developed by Mitsubishi Heavy Industries and Kansai Electric Power Co. (Iijima, 1998). Their technology is a chemical absorption (amine-based)
system using advanced energy efficient solvents and packing, and is believed to be among the best available of its kind (Wong et al, 2000). Reported costs were modified as appropriate to account for recent increases in energy prices, additional maintenance requirements, and a higher fixed capital charge rate.

The total capture cost, represented by the equations below, is based on the specific characteristics of the power plant (e.g., fuel and plant type, capacity, capacity factor, and emissions stream) and the performance of the capture technology. It also includes the cost of compressing the CO₂ to typical pipeline pressures.

\[
CaptureCost = a_i + \frac{b_i \times \text{PeakHourlyCaptureRate}^c_i}{\text{AnnualCO}_2\text{Capture}}
\]

where:

\[
\text{PeakHourlyCaptureRate} = (\text{CO}_2\text{Emissions}/(8760 \times \text{CapFactor})) \times \text{CaptureFraction} \]

\[
\text{AnnualCO}_2\text{Capture} = \text{CO}_2\text{Emissions} \times \text{CaptureFraction} \]

\[
\text{CO}_2\text{Emissions} = \text{Annual emissions of CO}_2 \text{ from plant } i \text{ in tons} \]

\[
\text{CapFactor} = \text{Average capacity factor for plant } i \]

\[
\text{CaptureFraction}_i = \text{Capture efficiency of the system for specified plant type} \]

\[
a_i = \text{Levelized cost of utilities, chemicals, operations, and maintenance (O&M)} \]

\[
b_i = \text{Annualized capital cost factor, including fixed charge rate} \]

\[
c_i = \text{Capital cost scaling factor} \]

**Transport**

The preferred means for transporting CO₂ over appreciable distances is via pipeline. Currently there exists over 2,300 miles of dedicated CO₂ pipeline infrastructure in the U.S. for delivering CO₂ to EOR fields. The pipeline sizing algorithm used was based on published data for CO₂ pipelines and flow rates for captured CO₂ (Brown et al, 1993). Recent natural gas pipeline construction data were used to develop costs, including materials, labor, rights of way, and other miscellaneous costs (True, 2000). A factor was used for converting straight-line distance as calculated by the GIS into a more reasonable pipeline distance, as was an adder to account for the uncertainty in locating an acceptable injection site within a targeted formation.

\[
\text{TransportCost} = e_i \times (\text{distance} + f_i) \times \left( \frac{g_i \times \text{PeakHourlyCaptureRate}^h_i}{\text{AnnualCO}_2\text{Capture}} \right)
\]

where:
distance = Straight line distance between selected source and sink

e_i = Scaling factor to convert straight-line distance into estimated pipeline distance

f_i = Distance adder to account for uncertainty in locating optimal delivery / injection site.

g_i = Annualized pipeline capital cost factor including fixed charge rate and annual O&M

h_i = Pipeline capital cost scaling factor

**Disposal**

The cost of CO2 injection and the associated requirements to ensure stable long-term storage remain the least defined of all the costs. At this point, some rather generic disposal costs were selected to represent the cost to inject CO2 into each of the possible formation types. Estimates of cost per ton of CO2 injected were made via a wide survey of the literature for reported experience in EOR and ECBM applications and assessments for disposal in deep saline formations (examples include Stevens et al, 1998, IEA, 1996, Gupta et al, 2001). Nevertheless, a rigorous cost algorithm was implemented to accept more detailed data as they are developed.

\[
\text{Disposal Cost} = j_i + \frac{k_i \times \text{Peak Hourly Capture Rate}^i}{\text{Annual CO}_2 \text{ Capture}}
\]

where:

\( j_i = \text{Levelized disposal/injection costs, including utilities, O&M} \)

\( k_i = \text{Annualized disposal/injection cost factor including fixed charge rate} \)

\( l_i = \text{Disposal/injection capital cost scaling factor} \)

**Application**

The value of the CO2-GIS with its integrated screening capability goes beyond visualization of emissions sources and potential disposal sites. The real value is in the ability to identify least-cost sequestration pathways in support of carbon management analysis and decision making. There are many ways to use the model to help utilities and government agencies identify possible solutions to the emissions problems they are beginning to face. It can also help them to identify the options that may be available and stimulate more serious thought regarding how to best manage emissions in an integrated manner.

The solution for one plant or company may well be different than that for another, depending upon such things as plant design and operating characteristics, age, location, and proximity to potential sequestration sites. Anything from a single plant to the complete generation asset base of a company or region could be examined by the system to provide key insights into available options and implications.
Running the Cost Estimator

Running the cost estimator from within the CO2-GIS is a very simple process. The target set of power generating units is first selected, be it a single unit, all plants in a particular region, or all plants across the country. Then the cost estimator tool is accessed via the button on the toolbar. From the window that opens (shown as Figure 1), the types of geologic sequestration options to consider in the analysis are selected (e.g., EOR, deep unmineable coal seams, deep saline aquifers). At this point the cost assumptions can be reviewed and modified if desired. A search radius is specified to limit the search for sinks to a reasonable distance around each plant and pressing “Calculate” starts the analysis process.

![Figure 1: Economic Screening Analysis Window](image)

The system identifies each plant/sink pair meeting the specified criteria and calculates the distance between them, along with the set of costs described above. The total cost for the capture, transport, and sequestration of CO2 from the plant is reported on an output table along with other parameters describing the plant and selected sink. An example of the output is shown in Table 1 for two sample generating units in Oklahoma having access to several different disposal options within the specified search radius. Depending upon the use of the credit factor, for the value of the CO2 or produced oil or methane, the resulting costs may in some cases be negative (indicating net savings or revenue), as in this case for the EOR scenarios.

<table>
<thead>
<tr>
<th>Plant*</th>
<th>Genunit</th>
<th>State</th>
<th>Owner*</th>
<th>Sinktype</th>
<th>Sink Name</th>
<th>Distance (miles)</th>
<th>Fuel</th>
<th>SO2 Controls?</th>
<th>CO2 Emissions (tons)</th>
<th>Total Cost ($/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant1</td>
<td>1</td>
<td>OK</td>
<td>Owner1</td>
<td>CO2 EOR - Current</td>
<td>Bradley Unit</td>
<td>114.2</td>
<td>Coal</td>
<td>No</td>
<td>3,459,088</td>
<td>-21.69</td>
</tr>
<tr>
<td>Plant2</td>
<td>1</td>
<td>OK</td>
<td>Owner2</td>
<td>CO2 EOR - Current</td>
<td>Bradley Unit</td>
<td>124.3</td>
<td>Nat. Gas</td>
<td>No</td>
<td>709,556</td>
<td>-1.22</td>
</tr>
<tr>
<td>Plant1</td>
<td>1</td>
<td>OK</td>
<td>Owner1</td>
<td>CBM Fields</td>
<td>Cherokee Basin</td>
<td>26.6</td>
<td>Coal</td>
<td>No</td>
<td>3,459,088</td>
<td>14.64</td>
</tr>
<tr>
<td>Plant1</td>
<td>1</td>
<td>OK</td>
<td>Owner1</td>
<td>Deep Saline Aquifers</td>
<td>Arbuckle</td>
<td>0.0</td>
<td>Coal</td>
<td>No</td>
<td>3,459,088</td>
<td>26.88</td>
</tr>
<tr>
<td>Plant2</td>
<td>1</td>
<td>OK</td>
<td>Owner2</td>
<td>CBM Fields</td>
<td>Cherokee Basin</td>
<td>0.0</td>
<td>Nat. Gas</td>
<td>No</td>
<td>709,556</td>
<td>27.79</td>
</tr>
<tr>
<td>Plant2</td>
<td>1</td>
<td>OK</td>
<td>Owner2</td>
<td>Deep Saline Aquifers</td>
<td>Arbuckle</td>
<td>0.0</td>
<td>Nat. Gas</td>
<td>No</td>
<td>709,556</td>
<td>41.79</td>
</tr>
</tbody>
</table>

*Actual plant and owner names withheld for this illustration
Sequestration Options for Newest 20% of U.S. Coal-Fired Plants

To provide an example of the capabilities of the CO2-GIS, we examine the set of power plants that would likely be initial targets for retrofit capture systems – newer coal-fired plants. Of the 794 coal-fired generating units in the United States, 163 were built since 1980. The total capacity of these plants is 85.9 gigawatts, representing 19% of all U.S. fossil-fired power generation capacity. Individual unit nameplate capacities range from 102 MW to 1,426 MW, with an average of 527 MW. Together, these plants emit some 632 million tons of CO2 to the atmosphere each year, or 25.4% of all U.S. electric utility emissions. The plants, as depicted in Figure 2, are well dispersed throughout much of the country.

If a strategy needed to be developed today to capture the CO2 off the stack of some of these plants and sequester it in geologic formations, the CO2-GIS would be a valuable tool to use in the process. By simply looking at the overlay of the 163 generating units and the various sequestration options (shown in Figure 3) it is possible to see immediately that many of the plants are located quite close to potential sinks. In fact, a large number of the coal plants sit directly over priority deep saline formations (the green textured areas on the map) and deep coal seams (shown as dark grey solid areas). A smaller number are within close proximity to existing and planned CO2-EOR projects (represented by purple dots and red oil derricks, respectively).
However, identifying which plants are most attractive to capture from, and which sequestration pathway is most economical for each of those plants, is more difficult. Completing the analysis with the CO₂-GIS economic screening capability, we are able to quickly identify and rank the most cost-effective pairs of plants and sinks. Running the screening analysis on this set of plants with a search radius of 100 miles, we find that 119 of the 163 units are located within that distance to one or more possible geologic sequestration sites. The relatively short search radius was specified because concerns over the siting of dedicated CO₂ pipelines and their high construction costs will likely limit practical distances, at least in the near term.

Perhaps not surprisingly, capture and sequestration makes the most economic sense for large generating units with high capacity factors located close to EOR fields. EOR and ECBM are the two known methods of geologic sequestration that result in a marketable by-product. The value of the oil produced per unit of injected CO₂ in EOR is higher than the value of methane produced from ECBM (at about a 3.5:1 ratio at recent energy prices); therefore, on the basis of economic return alone, EOR tends to be the most attractive geologic disposal option. However, in this example only 9 plants elect to pipe their CO₂ to such fields, as shown in Table 2. This is because they are the only plants in the group having identified EOR opportunities within a 100-mile radius. In fact, most of the plants opt for other disposal options: 75 for deep unmineable coal seams and 35 for deep saline formations.
Table 2: Results from Economic Screening

<table>
<thead>
<tr>
<th>Disposal Type</th>
<th>#Plants</th>
<th>Million Tons CO2/yr</th>
<th>Avg. Cost ($/ton)</th>
<th>Total Miles of Pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOR Fields</td>
<td>9</td>
<td>34</td>
<td>-$30.26</td>
<td>514</td>
</tr>
<tr>
<td>Deep Coal Seams</td>
<td>75</td>
<td>330</td>
<td>$9.96</td>
<td>1,580</td>
</tr>
<tr>
<td>Deep Saline Formations</td>
<td>35</td>
<td>113</td>
<td>$25.64</td>
<td>1,200</td>
</tr>
</tbody>
</table>

If each of these 119 generating units were retrofitted with a capture system, some 430 million tons of CO2 emissions could be avoided annually. The total cost per ton varies significantly, depending on plant characteristics, distance to and type of sequestration, but range from $-33.55 to $37.71. The average cost for EOR disposal is $-30.26; $9.96 for deep coal seams, and $25.64 for deep saline formations. If each of these generating units sent captured CO2 to the selected least-cost sequestration target, the equivalent of about 1.5 times the current total length of U.S. dedicated CO2 pipeline would be required. The ultimate length would likely be less than this, however, with a well-planned transmission system that takes advantage of the close proximity of several of the plants, allowing them to tie into the same trunk line.

Of course there are other considerations besides the criteria used in this analysis that would also help shape any final decisions made on these issues. For example, as long as cheap CO2 is extracted from large underground formations and piped to the oil fields of the Permian Basin and elsewhere, it may be difficult to sell appreciable volumes of captured CO2 in those regions. Additionally, a deviation from current operating conditions or practice at a particular generating plant or injection location might alter the attractiveness of capture and sequestration for those sites. Further, new sequestration options will likely be identified and some current target formations may ultimately prove ill suited for stable long-term storage of CO2. Finally, the cost of capturing and transporting CO2 will likely change with experience and more robust system design and integration. Implementation of emissions taxes on CO2 alone would cause a large shift in the economic viability and necessity of capture and sequestration and the current status of each of these items and their impact on carbon management decisions should be reviewed over time.

Future Activities

A key driver for the development of the Battelle CO2-GIS and integrated economic screening capability has been the dynamic and evolving nature of this area of research. The ease of updating the CO2-GIS enables us to keep up-to-date with many of these changes as the concept and practice of carbon capture and sequestration unfolds. It is not intended to try to provide all the answers, but rather provide valuable insight and information on the source/sink relationships and contribute to the base of knowledge needed in the effort to stabilize atmospheric carbon dioxide levels.
In order to maintain its usefulness as the fields of carbon capture and sequestration develop, the CO2-GIS will also need to evolve. It will need to look beyond existing power generation as the primary source of CO2. It will need to be able to provide insights into the siting and selection of advanced power technologies, both with and without capture and sequestration components. It will also need to include additional large CO2 point sources, such as refineries, gas processing plants, and cement plants. It will need to develop capacity curves for the main storage options and use that information in its decision process, along with the presence and price levels of competing sources. Additional limitations will emerge as we go forward and learn more about the physical, geochemical, and economic implications of responding to the threat of climate change. And additional changes and enhancements will follow in order that the Battelle CO2-GIS remains at the forefront of carbon management decision analysis.

References


