A Systems Perspective for Assessing Carbon Dioxide Capture and Storage Opportunities

by

Nisheeth Singh
BE, Mining Engineering, National Institute of Technology, Rourkela, INDIA
MS, Mining Engineering, Southern Illinois University, Carbondale, IL, USA

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Signature of Author____
Nisheeth Singh
System Design and Management Program
May 2004

Certified by ____
Howard Herzog
Principal Research Engineer, Lab for Energy & Environment, MIT
Thesis Supervisor

Accepted by ____
Tomas J. Allen
Co-Director, LFM/SDM
Howard W. Johnson Professor of Management

Accepted by ____
David Simchi-Levi
Co-Director, LFM/SDM
Professor of Engineering Systems

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LIST OF ABBREVIATIONS

Abbreviation	**Meaning**
CCS	Carbon capture and storage
CO_2	Carbon dioxide
DOE	United States Department of Energy
DSS	Decision Support System
eGRID	Emissions and Generation Resource Integrated Database
EOR	Enhanced oil recovery
EPA	Environmental Protection Agency (US)
EU	European Union
GESTCO	European Potential for Geological Storage of Carbon Dioxide from Fossil Fuel Combustion
GHG	Greenhouse gas
GIS	Geographical information system
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LFEE	Laboratory for Energy and the Environment (at MIT)
MIT	Massachusetts Institute of Technology
NETL	National Energy Technology Laboratory (US DOE)
NO_X	Collective term for different oxides of Nitrogen
SERCSP	South East Regional Carbon Sequestration Partnership
SO_2	Sulfur dioxide
UN	United Nations
UNEP	United Nations Environmental Program
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
WCRCSP	West Coast Regional Carbon Sequestration Partnership
WMO	World Meteorological Organization

ABSTRACT

Even as the acceptance of the fossil fuel greenhouse effect theory continues to grow amongst academics, statesmen and plebeians alike, the early adopters have already engaged in pre-emptive research activities aimed at mitigating the effects of such greenhouse gases. The focus of one such effort is on the capture and storage of CO_2 (carbon dioxide) from anthropogenic fixed source emissions. This effort can be broken down into a few broad categories such as terrestrial, ocean and geologic sequestration. Geologic sequestration refers to all activities geared towards the capture and storage of CO_2 under the surface of the earth in diverse 'reservoirs' such as deep saline formations, depleted oil and gas wells and unmineable coal seams to name a few. This investigation develops a systems perspective for assessing carbon dioxide capture and storage (CCS) opportunities within the realm of geologic sequestration.

While multiple concurrent research activities continue to explore CCS opportunities from various perspectives, efforts at a systems analysis of the overall picture are just beginning. A systems view describing methodologies to integrate a variety of CCS data to assess potential sequestration opportunities is at the heart of this study. It is based on research being conducted at the Massachusetts Institute of Technology (MIT) under sponsorship of the United States Department of Energy (DOE). Using a Geographic Information System (GIS) and publicly available data, a detailed characterization of CO_2 sources and reservoirs are being developed. A source-reservoir matching process will be implemented which begins with quantifying the 'capturability' of a CO_2 source, a function of the purity, volume and several site specific considerations. Next, the potential proximate reservoirs are identified and then ranked based on transport options, type, capacity, cost, regulatory considerations

and political sensitivity. All the above criteria will be spatially represented in the GIS and can be overlaid to produce a composite picture identifying the potential areas which would represent the maximum probability of success in sequestration efforts. A rigorous systems engineering approach will be adopted throughout the investigation. Novel tools such as the Object-Process CASE (OPCAT) tool will be used to model the complex and interdisciplinary system. A comprehensive systems modeling and engineering tool, it allows the representation of function, structure and behavior in a single model.

Ultimately, the methodologies developed will be integrated and utilized in a case study to illustrate the methodology of evaluating CCS options for a given set of sources. A region in Mississippi has been identified for this model case-study. The methodology will be applied at a later time to evaluate CCS potential in the South East Regional Carbon Sequestration Partnership (SERCSP) and the West Coast Regional Carbon Sequestration Partnership (WCRCSP).

1: INTRODUCTION

1.1: What is the Greenhouse Effect?

News headline on The Environmental News Network[1]: *"Thursday, March 15, 2001 – Observations from satellites support a new theory that carbon dioxide and other emissions are to blame for global warming, confirming what some climate models have been implying, that Earth's 'greenhouse' effect increased between 1970 and 1997."* So what is actually the greenhouse effect? While the world's climate has always varied naturally, the vast majority of scientists now believe that rising concentrations of "greenhouse gases" in the earth's atmosphere, resulting from economic and demographic growth over the last two centuries since the industrial revolution, are overriding this natural variability and leading to potentially irreversible climate change. The importance of energy as a tool for meeting the needs for economic and demographic growth has been acknowledged at every major United Nations conference in the 1990s, starting with the Rio Earth Summit (UN Conference on Environment and Development) in 1992[2]. Greenhouse gases – especially carbon dioxide (CO_2), the most abundant from human sources – act like a blanket over the Earth's surface, keeping it warmer than it would otherwise be. The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), released in 2001, confirms that "an increasing body of observations gives a collective picture of a warming world" with "new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities"[3].

While this issue of the greenhouse effect has been the subject of discussion amongst academics for well over a decade, it has achieved global significance amongst academics, statesmen and plebeians alike over the last decade. This steep acceleration in the discussion and research of the greenhouse effect was probably precipitated by the formation of the FCCC in 1992. The FCCC was established in response to the reports from the IPCC and adopted by over 150 countries as a blueprint for precautionary action. The main objective of the FCCC (Article 2) was to achieve a stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system[4]. In order to achieve this, the party nations were committed to drawing up national programs to return emissions of greenhouse gases to 1990 levels by the year 2000.

1.2: Efforts to Mitigate the Greenhouse Effect

Though there still exists a small minority of skeptics questioning the existence of the greenhouse effect, research activities aimed at mitigating the greenhouse effect have taken off at varying paces primarily funded by governments and private research interests. For the fiscal year 2004, the proposed budget of United States calls for a 15 percent increase in funding for climate change-related programs bringing total U.S. spending on climate change to \$4.3 billion and to its highest level ever to date[5]. To tackle the issue of climate change, a portfolio of measures are being researched and adopted globally. CO_2 accounts for the majority of greenhouse gases released and is currently responsible for 60% of the greenhouse effect[6]. Thus, the issue of tackling anthropogenic fixed source emissions of CO_2 assumes primary importance. Such emissions of CO_2 are primarily created by the burning of fossil fuels such as coal, oil and gas for the production of energy. Efforts at mitigating the effects of CO_2 include developing alternatives to fossil fuels such as renewables and nuclear energy, better technology for more efficient power production & energy use and carbon dioxide capture and storage (CCS).

1.3: What is Carbon Sequestration?

Herzog and Golomb define carbon sequestration “as the capture and secure storage of carbon that would otherwise be emitted to, or remain, in the atmosphere”[7]. CCS refers to technologies which involve the capture of carbon dioxide from large stationary sources and artificial injection of the CO_2 into target reservoirs with the express purpose of storing the CO_2 in those reservoirs. The two distinct areas this can be studied under include

- Capture: This refers to technologies enabling the capture of CO_2 from sources such as power plants, gas processing plants, industrial plants etc.
- Storage: Once captured, the CO_2 is directed towards storage in different kinds of reservoirs.
    - Geologic sequestration refers to the capture of CO_2 and its long-term storage in geologic formations such as oil and gas reservoirs, unmineable coal seams, and deep saline formations
    - Ocean sequestration refers to the capture of CO_2 and its subsequent storage in ocean water. CO_2 is soluble in ocean water and can serve as a reservoir for long-term storage
    - Biological sequestration refers to increasing CO_2 fixation through photosynthesis, slowing down or reducing decomposition of organic matter, and changing land use practices can enhance carbon uptake in natural CO_2 reservoirs such as soils and vegetation

As described, geologic sequestration refers to all activities geared towards the capture and storage of CO_2 under the surface of the earth in diverse ‘reservoirs’ such as deep saline formations, depleted oil and gas wells and unmineable coal seams to name a few. This investigation considers and concerns CCS opportunities within the realm of geologic sequestration only.

1.4: A Systems Perspective

While multiple concurrent research activities continue to explore CCS opportunities from various perspectives, efforts at a systems analysis of the overall picture are just beginning. A systems perspective becomes necessary due to the following reasons:

- Multiple research efforts
- Research thrusts in different directions
- Few attempts at integrating all the efforts

A systems perspective will:

- Identify interacting effects
- Recognize barriers and enablers
- Identify research areas needing extra attention
- Enable a meaningful comprehensive evaluation of CCS options

A systems view describing methodologies to integrate a variety of CCS data to assess potential sequestration opportunities is at the heart of this study. It is based on research being conducted at the Massachusetts Institute of Technology (MIT) under sponsorship of the United States Department of Energy (DOE). This research at MIT is focused around developing a Geographic Information System (GIS).

A GIS organizes and stores information as a collection of thematic layers that can be linked by geography. Each layer contains features having similar attributes, like power plants or industrial facilities. Furthermore, complex custom queries can be created and embedded in the GIS to display layers with attributes that are the result of data transformation from underlying layers. This flexibility allows the GIS to spatially represent any set of regions with practically any possible combination of select parameters as long as sufficient underlying data is available.

1.5: A Brief Outline of the Thesis

The development of this philosophy follows a logical approach with several distinct steps that take on the form of separate chapters and which are summarized below.

Introduction: This chapter lays the foundation for the thesis by providing a primer on climate change and the greenhouse effect and a brief discussion on the efforts to mitigate them.

***History and Background**:* An in-depth and comprehensive literature survey covering different research activities to date and original work related to the thesis. Begins with the bigger picture but quickly zooms into the research on geologic sequestration.

Carbon Dioxide Source Capture Aspects: Next, the different sources of CO_2 are characterized with special attention to the 'capturability' of a given source, a function of the purity, volume and other site specific considerations.

Carbon Dioxide Storage Reservoirs: Next, the potential reservoirs are identified and then ranked based on transport options, type, capacity, cost, regulatory considerations and political sensitivity.

Carbon Dioxide Transportation: This chapter discusses the major mode of CO_2 transportation today – pipeline transportation. A model for the cost of building pipelines and the parameters determining this cost are presented. Major parameters include throughput, quality of CO_2, length, topography, pressure, right-of-way issues amongst others.

System Evolution and Sample Problem: The actual evolution of the systems methodology is presented in this chapter. A visual model is developed for the entire system using the Object-Process CASE (OPCAT) tool to model the complex and interdisciplinary system. This chapter then integrates all the major steps outlined in the previous chapters in a sample problem. This is to illustrate the methodology of evaluating CCS options for a given set of sources. A region located mostly in the state of Mississippi and covering parts of Alabama and Louisiana in the US was identified for this model case study. The methodology will be applied at a later time to evaluate CCS potential in the South East Regional Carbon Sequestration Partnership (SERCSP) and the West Coast Regional Carbon Sequestration Partnership (WCRCSP).

Conclusion and Recommendations: The vision for the final version of the system is summarized here. Due to data limitations, recommendations would include future work needed to conduct a more complete systems analysis.

2: HISTORY AND BACKGROUND

This chapter details the background and history of CCS. Since the science of CCS is relatively very recent compared to traditional sciences, little has been established and accepted amongst the scientific community as the holy grail of CCS and it continues to be a particularly dynamic and evolving field of study as research in this field progresses and new ground is broken. Rather than try to reconcile and integrate different schools of thought in CCS technologies and present a unified and sometimes conflicting generic almanac, some typical research projects are presented here to provide a more hands-on feeling for where the research stands today.

As mentioned in the previous chapter, the GIS being developed at MIT provides the framework to develop a systems analysis of CCS options. Thus, a brief description of a general GIS is in order and will be presented along with a more detailed discussion of the GIS being developed at MIT.

2.1: History

The practice of pumping CO_2 into geological formations has been around for three decades now, mostly in oil and gas reservoirs, albeit not with the primary goal of storing CO_2 but rather using it as an injectant to pump oil and gas out of reservoirs. This process is known as Enhanced Oil Recovery (EOR). To this end, the focus of research was on the technical aspects of injecting CO_2 and recovering the resource rather than on the capturability of the CO_2 source and the effect it would have in reducing GHG emissions. Moreover, the stability of the injected CO_2 was not at stake once the resource had been extracted and hence monitoring was not a primary concern. However, these activities established a starting point for geologic sequestration activities, especially in oil and gas reservoirs.

Similar to the history of sequestering carbon dioxide in oil and gas wells, in the past, CO_2 and other gases such as Nitrogen (N_2) or even a mixture of gases have been used to recover methane from unmineable coal seams in a process known as Enhanced Coalbed Methane Recovery or ECBMR in short. Once again, though these efforts were primarily motivated by the prospect of recovering methane and very limited in nature, they lay the foundation for CCS activities in deep unmineable coal seams. Efforts at sequestering CO_2 in deep saline formations are much more recent and consequently fewer in number. Descriptions of a few selected projects in the three broad categories of geologic sequestration follow to provide a quick overview of past and current research activities in the area.

2.2: Storage in Oil and Gas Reservoirs

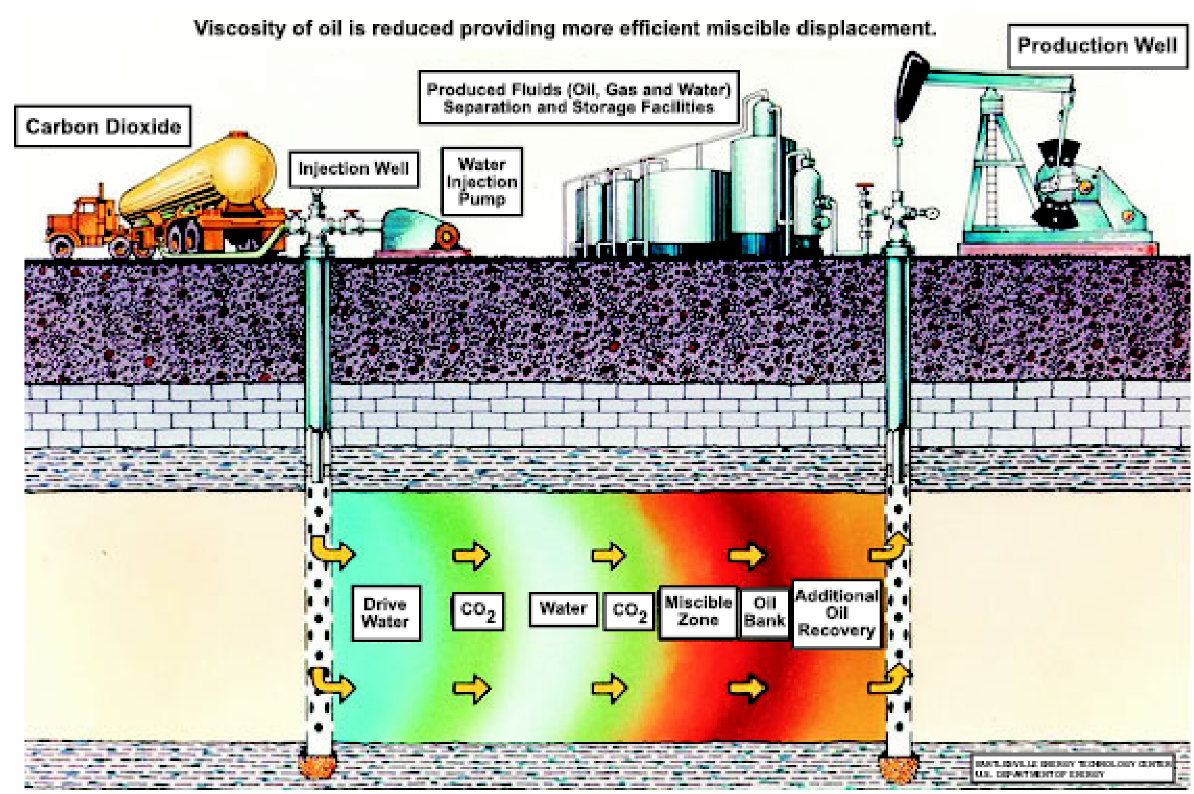

Figure 1: Schematic of CO_2 EOR (Courtesy NETL Program Fact Sheet on EOR[8])

2.2.1: Enhanced Oil Recovery (EOR)[8]

As mentioned earlier, EOR refers to techniques that allow increased recovery of oil in depleted or high viscosity oil fields. This has the potential to not only increase the yield of depleted or high viscosity fields, but also to sequester CO_2 that would normally be released to the atmosphere. In general terms, carbon dioxide is flooded into an oilfield through a number of injection wells drilled amidst producing wells in different complex patterns. Injected at a pressure equal to or above the minimum miscibility pressure (MMP), the CO_2 and oil mix and form a liquid that easily flows to the production well. Pumping can also be enhanced by flooding CO_2 at a pressure below the MMP, swelling the oil and reducing its viscosity. This process is illustrated in Figure 1

In 2000, EOR projects produced a total of 780,000 barrels of oil per day, almost 12 percent of the total U.S. production. Although CO_2 EOR comprises only a small portion of all EOR being performed in the U.S., maturing oil fields and narrow profit margins make this method of resource recovery increasingly attractive to industry. The U.S. has been a leader in developing and using technologies for CO_2 EOR; currently about 96% of EOR with CO_2 is preformed in the U.S.

2.2.2: Weyburn CO_2 EOR Project

In October 2000, EnCana began injecting CO_2 into a Williston Basin oilfield (Weyburn) in order to boost oil production. The Weyburn oilfield covers over 70 square miles in southeastern Saskatchewan and is one of the largest medium-sour crude oil reservoirs in Canada, containing approximately 1.4 billion barrels of original oil in place[8]. Overall, it is anticipated that some 20 Mt of CO_2 will be permanently sequestered over the lifespan of the project and contribute to the production of at least 122 million barrels of incremental oil from a field that has already produced 335 million barrels since its discovery in 1955. The gas is being supplied via a 205 mile pipeline stretching from the lignite-fueled Dakota Gasification Company Great Plains Synfuels plant site in North Dakota. At the plant, CO_2 is produced from a Rectisol unit in the gas cleanup train of the coal-fired plant. Sales of the CO_2 add about $30 million of gross revenue to the gasification plant's cash flow each year. Researchers collected background information prior to the flooding of the field with CO_2 allowing for comparison of field characteristics before and after CO_2 injection and enhancing understanding of interactions and relationships between oil recovery and CO_2 storage. The IEA Weyburn CO_2 Monitoring and Storage Project is coordinated by 20 research organizations in the U.S., UK, France, Italy and Denmark, including the U.S. DOE/NETL Carbon Sequestration Program, and co-administered by the Petroleum Technology Research Centre, Natural Resources Canada, Saskatchewan Industry and Resources, the Saskatchewan Research Council, the University of Regina and IEA GHG R&D Programme.

2.2.3: Rangely CO_2 EOR Project

Chevron's Rangely Weber field in Colorado is one of the largest EOR projects using anthropogenic CO_2. Carbon dioxide for this flood is purchased from the ExxonMobil LaBarge natural gas processing facility in Wyoming and then transported via pipeline to the field. The Rangely CO_2 flood is comprised of an array of 341 production wells and 209 injection wells and extends over an area of 61 km^2. CO_2 injection began at Rangely in 1986 and leakage of CO_2 via wellbores or through the reservoir cap is considered to be negligible. Foams, gels and other strategies are used to improve conformance and reduce premature CO_2 breakthrough. Monitoring wells are used to track movement of injectant within the reservoir, and reservoir simulations estimate ultimate CO_2 sequestration at the Rangely field. By the time the project is completed, an estimated total of 25 Mt (472 Bcf) of CO_2 will have been injected.

2.3: Sequestration in Deep, Unmineable Coal Seams[9]

One approach to sequestering carbon dioxide (CO_2) is to inject it into deep, unmineable coal seams. A particular advantage of coal seam sequestration is that coal seams can store several times more CO_2 than the equivalent volume of a conventional gas reservoir because coal has a large surface area. Advanced Resources International[10], a leading technology development and oil and gas consulting firm and their partners are using the only long-term, multi-well ECBMR projects that exist in the world today to evaluate the viability of storing CO_2 in deep, unmineable coal seams. The two existing ECBMR pilots are located in the San Juan Basin in northwest New Mexico and southwestern Colorado. The knowledge gained from studying these projects is being used to verify and validate gas storage mechanisms in coal reservoirs, and to develop a screening model to assess CO_2 sequestration potential in other promising coal basins of the U.S.

The two field pilots, the Allison Unit (operated by Burlington Resources) and the Tiffany Unit (operated by BP America) are demonstrating CO_2 and nitrogen (N_2) ECBMR recovery technology respectively. The interest in understanding how N_2 affects the process has important implications for power plant flue gas injection, since N_2 is the primary constituent of flue gas. Currently, the cost of separating CO_2 from flue gas is very high. This project is evaluating an alternative to separation by sequestering the entire flue gas stream. Another reason for considering CO_2/N_2 is that N_2 is also an effective methane displacer, improving methane recoveries and further decreasing the net cost of CO_2 sequestration. The

Allison Unit pilot area, which has been in operation since 1995, includes 16 producer wells and 4 injector wells. The Tiffany Unit pilot area which has been in operation since 1998 is made up of 34 producer wells and 12 injector wells. This demonstration project is providing valuable new information to improve the understanding of formation behavior with CO_2 injection, the ability to predict results and optimize the process through reservoir modeling.

2.4: Sequestration in Deep Saline Formations

Deep saline formations which represent a significant portion by volume of sedimentary basins have the potential to store CO_2 by three main mechanisms:

- hydrodynamic trapping of a CO_2 plume (primary mechanism)
- solubility trapping through dissolution in the formation water
- mineral trapping through geochemical reactions with the formation fluids and rocks

In addition, a CO_2 plume may be trapped in structural and/or stratigraphic traps along the flow pathway, other than and including associated oil and gas reservoirs.

Several large saline formations underlie the United States, but there is no injection of CO_2 into them yet. In Europe though, one million tons CO_2 per year are being injected in the saline formation at the Sleipner natural gas production field in the North Sea. A significant body of data on domestic brine formations has been compiled by NETL, the University of Texas at Austin, and others.

2.4.1: Saline Aquifer CO_2 Storage (SACS)[11,12]

The Sleipner project is the world's first commercial-scale storage of CO_2 in a saline formation for mitigation of climate change. The CO_2 in this case is an unwanted by-product of natural gas production from Sleipner West gas field in the North Sea. The CO_2 is injected into a large, deep saline reservoir, the Utsira formation 800 m below the bed of the North Sea. Statoil operates the Sleipner field on behalf of a group of partners. Injection of CO_2 started in October 1996 and a special project, the SACS project, was established separately in 1999 to monitor and research the storage of CO_2 in this unique facility. A schematic of the SACS project is illustrated in Figure 2.

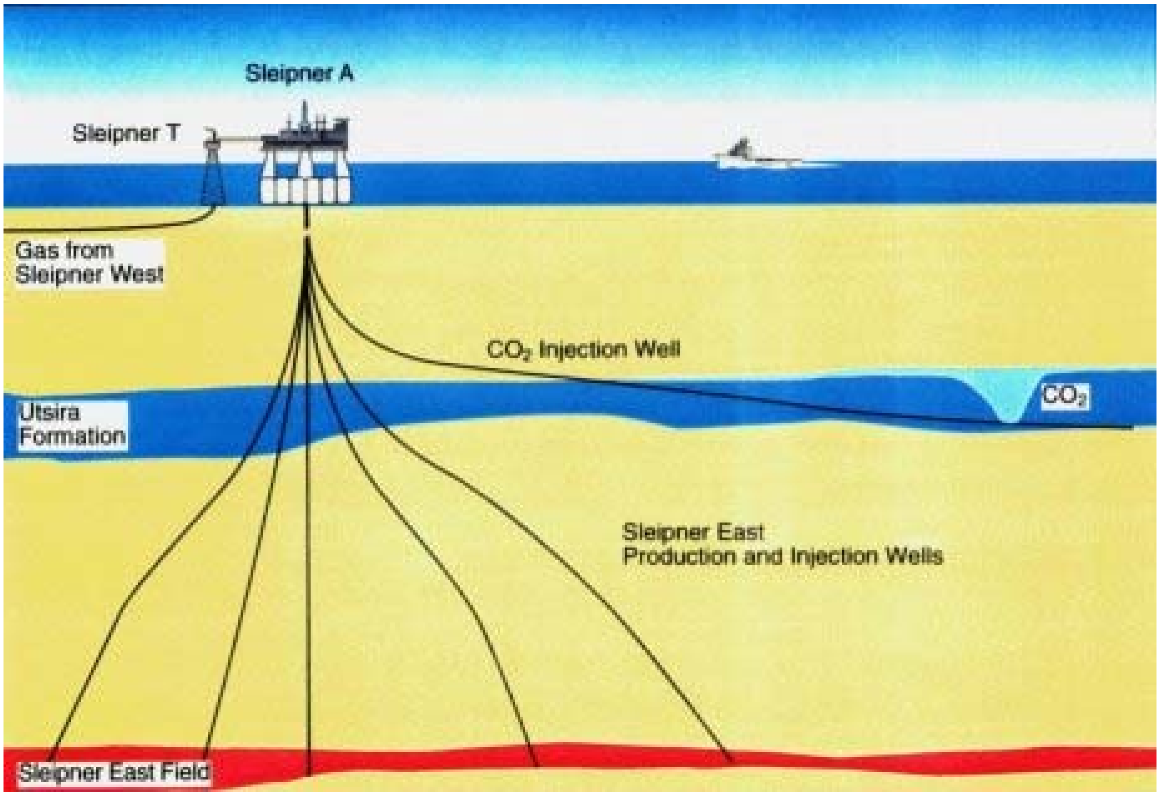

Figure 2: Schematic of the SACS project (Courtesy IEA SACS Project Website)

To date, nearly 5 million tonnes of CO_2 have been injected without any significant operational problems observed in the capture plant or in the injection well. Since monitoring is a high priority for this project, the project has had significant success with the demonstration that conventional time lapse seismic data can be a successful monitoring tool for CO_2 injected into a saline formation. A reservoir simulation model that was specifically developed for this project was validated against this seismic data with good correlation. This model indicates that most of the CO_2 accumulates in one bubble under the cap seal of the formation a few years after the injection is turned off. The CO_2 bubble spreads laterally on top of the brine column and the migration is controlled by the topography of the cap seal only. The model indicates that diffusion of CO_2 from the gas cap into the underlying brine column will have a pronounced effect. The brine on top of the column, which becomes enriched in CO_2, is denser then the brine below which sets up convection currents maintaining a large concentration gradient near the CO_2-brine interface, enhancing the dissolution of CO_2. The initial simulations indicate that bubble will reach a maximum size in probably less than 300 years. After this time, dissolution is the dominating effect on bubble extension and the bubble will gradually shrink and finally disappear around 4000 years.

2.4.2: Frio Brine Pilot Project[13,14]

As mentioned earlier, even though there have been no studies conducted on injecting and storing CO_2 in saline formations in the US on a commercial scale, a few pilot scale projects have been commissioned and underway at the time of writing. One such project is the Frio brine pilot project, a field experiment to pioneer CO_2 injection for sequestration in a brine formation in the Texas Gulf Coast, USA.

This project will be the first US demonstration of CO_2 injection specifically for greenhouse gas reduction. Non-hydrocarbon-bearing high-permeability sandstones were identified as optimal targets for full-scale geologic sequestration because their large volumes and widespread distribution permit the large-volume disposal that is needed to impact CO_2 release volumes. This experiment in a brine/rock/CO_2 system was selected as the optimal site for CO_2 flow-simulation code validation and development of monitoring strategies. This setting is simpler than the typical CO_2 injection commercially conducted for EOR which contains one or more hydrocarbon phases that react strongly with the CO_2 and have been highly perturbed by past oil production practices.

2.5: Acid Gas Injection

Another technology that warrants mention in this chapter is acid gas injection. While primarily motivated by stricter hydrogen sulfide (H_2S) emission regulations, the technology developed provides an analog for CCS in different kinds of geological formations. Particularly common in Western Canada with a few projects in the US and the Middle East, acid gas injection basically refers to operations that capture CO_2 and H_2S from oil or gas streams produced from geological formations, compress and transport these gases to an injection well where they are injected into a different geological formation for disposal purposes. Thus, acid gas injection provides technology analogs in the three distinct areas of CO_2 sequestration: capture, transport and storage. The importance of these analogs is elevated by the fact that in many acid gas injection projects, CO_2 represents the largest component of the acid gas stream and in some cases over 90% of the total volume of the gas injected for storage[15]. So, in essence, a lot of acid gas injection projects fall directly under the category of CCS projects. Furthermore, the geological formations that are used for storage in acid gas injection projects are primarily depleted oil & gas reservoirs and deep saline formations – two of the most popular choices for storage within the realm of geologic carbon sequestration today.

2.6: Efforts at Systems Analysis

Since this investigation involves a systems analysis approach bringing together the different areas of CCS research, a section on the background and history of CCS activities would not be complete without a mention of the past and current efforts around the globe at conducting a systems analysis. While they have been few in number, valuable knowledge and guidelines can be drawn from these efforts. Moreover, a study of these efforts prevents redundancy and allow for alternate approaches and optimization of existing efforts.

2.6.1: APCRC GEODISC Program[16]

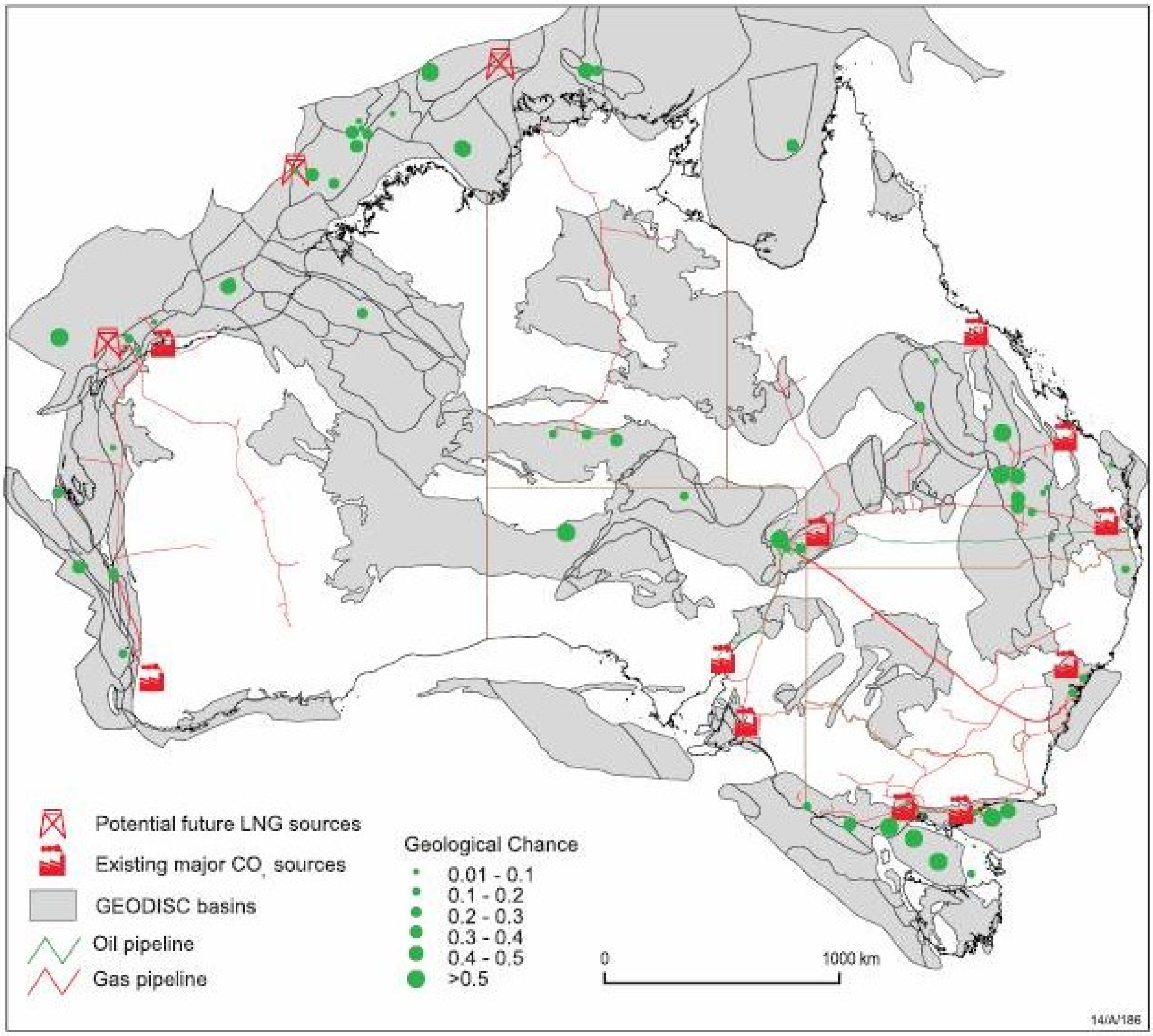

Figure 3: Distribution of the ESSCI chance in Australia (Courtesy APPEA Journal)

In Australia, geological sequestration encompassing all its different aspects has been the subject of research within the Australian Petroleum Cooperative Research Center's GEODISC program[17]. Under this program, a regional analysis examining the potential of geologic sequestration of CO_2 in all the sedimentary basins of Australia was undertaken and a portfolio of sequestration options across the country was created. The highlight of the project included the screening of 300 known sedimentary basins for storage and selecting 48 based on their geological characteristics including thickness, depth, stratigraphy& lithology and structural complexity. These storage sites were then relatively ranked based on five risk factors (assuming there was adequate data on each): storage capacity, injectivity potential, site details, containment and existing natural resources. The product of all these risk factors results in the Environmentally Sustainable Site for CO_2 Injection (ESSCI) index. A map illustrating the distribution of ESSCI chance in Australia is shown in Figure 3. Sources of CO_2 were regionalized into eight different 'emission nodes' by estimating the CO_2 emissions for the next two decades based on current emission trends. The estimates of CO_2 supply from these emission nodes and ESSCI indices for different sites facilitate the matching between sources and storage sites. Each storage site also underwent a preliminary economic assessment to estimate the costs of compression, pipeline transport, drilling injection wells and installing platforms. The integrated analysis identified where the most cost-effective storage sites occurred and where the greatest impact on reducing Australia's CO_2 emissions could be made.

2.6.2: GESTCO Project[18]

A Decision Support System (DSS) has been developed as part of part of an EU project, "European Potential for Geological Storage of Carbon Dioxide from Fossil Fuel Combustion" (GESTCO) to evaluate the technical and economical feasibility of CO_2 storage in the subsurface. With this system, CO_2 sequestration systems can be defined, consisting of a selection of CO_2 sources and reservoirs and a pipeline route. The DSS retrieves all relevant data needed to evaluate the whole chain from separation, transportation to storage from a database. This data is obtained by an extensive inventory including large industrial point sources and power plants, and, as possible geological storage sites, formations and abandoned gas and oil reservoirs.

The DSS is coupled to a database in which the data is stored obtained by the inventory. The interface of the DSS is based on a GIS that enables the user to define a CO_2 sequestration system by selecting CO_2 sources, capture technologies and reservoirs. An economical optimal transportation route is then established connecting the sources with the reservoirs. The DSS determines first if the storage potential of the selected sequestration is sufficient and if that is the case the costs of each link in the chain is calculated and added to arrive at total sequestration cost.

2.6.3: Batelle's CO_2-GIS[19,20]

In response to the need for a better understanding of carbon management options, Battelle developed a state-of-the-art Geographic Information System (GIS) focused on CCS opportunities in the United States. Known as the CO_2-GIS, it is an archive of information from various sources and includes information on fossil-fired power plants, EOR projects (both current and planned), ECBMR projects and coal basins with potential for coalbed methane production. In addition, natural geologic domes containing high purity CO_2, anthropogenic sources of CO_2 used for EOR and major CO_2 distribution pipelines are also included. Further, base map layers consisting of such items as state and county boundaries, major cities, highways, and water bodies are also included to provide spatial reference.

The CO_2-GIS provides an easy-to-use decision screening mechanism for CCS. The database contains a wealth of data critical to the analysis of such opportunities. Not only does it allow the storage of key data, but enables visual and interactive display and retrieval of the data as well as a wide array of analysis capability. Users are able to screen and query any combination of available parameters and view the spatial relationships of the results.

A unique feature about this project is that it has been funded from private sources as opposed to most other projects that stem from governmental initiatives. This renders the findings proprietary in nature and hence not generally accessible by the general public.

2.6.4: Play Analysis[21]

Although this study does not investigate the entire value chain of sequestration activities, there are important lessons to be learned about reservoir characterization from a systems analysis viewpoint.

Play analysis is used to classify conceptual models for petroleum reservoirs so that comparative studies can be undertaken. A play is defined as a conceptual geologic unit having one or more reservoirs that can be genetically related on the basis of depositional origin of the reservoir, structural or trap style, source rocks and hydrocarbon generation, migration mechanism, seals for entrapment, and type of hydrocarbon produced. Plays represent a geologically relatively homogeneous subdivision within the universe of petroleum reservoirs within a basin. Individual plays have unique geological features that can be viewed in terms of a conceptual model of geologic processes and depositional environments to explain and predict the distribution and characteristics of petroleum reservoirs. When grouped by plays, reservoirs show great similarity in terms of geological, engineering, and production characteristics.

The play concept has been used for organizing a vast amount of data available from Texas oil and gas reservoirs. Similar type of reservoir attributes are compiled for major oil and gas plays in the Gulf Coast region of Louisiana and Mississippi. Play average values are calculated from the available dataset. These play average attributes are used to characterize reservoir rock and fluid properties and evaluated to identify possible candidates for geologic sequestration and CO_2 EOR opportunities. Additional major geologic features such as faults along with cultural information are also provided.

2.7: GIS and MIT

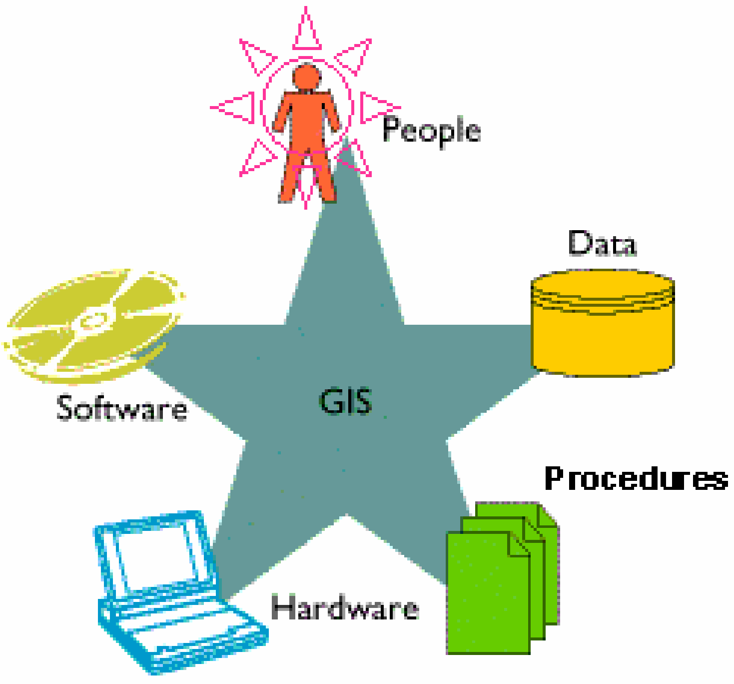

Figure 4: The five essential components of a GIS.

A GIS is a tool that can graphically represent information in a spatial context. It organizes and stores information as a collection of thematic layers that can be linked by geography. Each layer contains features having similar attributes, like power plants or industrial facilities that are located within the same geographic extent. Furthermore, complex custom queries can be created and embedded in the GIS to display layers with attributes that are the result of data transformation from underlying layers. This flexibility allows the GIS to spatially represent any set of regions with practically any possible combination of select parameters as long as sufficient underlying data is available. At the heart of every GIS are five essential components as shown in Figure 4.

As more information becomes available on the many varied components of a carbon management system and more and more people become interested in the potential of carbon capture and storage (CCS) technologies, the need has arisen for a systems analysis tool that can capture, integrate, manipulate and interpret this data. In response, the Laboratory for Energy and Environment (LFEE) at the Massachusetts Institute of Technology (MIT) is developing a Geographic Information System (GIS) for carbon management under the sponsorship of the US DOE as mentioned earlier. This GIS will store, integrate, and manipulate information relating to the components of carbon management systems. Additionally, the GIS can be used to interpret and analyze the effect of developing these systems.

3: CARBON DIOXIDE SOURCE CAPTURE ASPECTS

As mentioned in the previous chapter, the first step in the carbon sequestration process is the capture of the CO_2 from a source. Estimates of costs for capture tend to vary in wide ranges depending upon the kinds of assumptions made for the values of the different parameters determining the cost of CO_2 capture. Broadly speaking, the determining parameters are based on the kind of source, the operating and local conditions of the plant etc. Notwithstanding the wide ranges of cost estimates, it is still widely accepted that over 75% of the costs of geologic sequestration are associated with capture, separation and compression rather than the transportation and storage operations themselves. Nevertheless, there are opportunities to lower the net cost of sequestration by taking advantage of opportunities that require CO_2 while producing a commercial product that offsets the cost of sequestration with value-added benefits such as enhanced oil recovery (EOR) and enhanced coalbed methane recovery (ECBMR).

3.1: Why Capture Carbon Dioxide?

Before discussing the intricacies of CO_2 capture, an introduction to the motivation behind it is in order. The purpose of CO_2 capture is to produce a concentrated stream of CO_2 which can be transported and stored. Capture of CO_2 is best carried out at large point sources of emissions, such as power plants which currently account for over a third of global CO_2 emissions. Other large point sources include oil refineries, petrochemical, fertilizer and gas processing plants, steel works, cement plants, other chemical plants and pulp and paper mills.

In the broader context of reducing the greenhouse gas effect by reducing the concentration of CO_2 in the atmosphere, the relative cost and feasibility of capturing CO_2 from the sources mentioned must be evaluated. In theory, the entire gas stream from combustion processes could be stored, avoiding the need for CO_2 capture. However, for air-blown combustion, the amount of energy required to compress the flue gas to enable it to be transported and stored would make the process highly inefficient and consequently very expensive. Also, the percentage of CO_2 in flue gas is fairly low (4-15%) leading to very low effective storage capacities for CO_2 reservoirs. Since power plants using fossil fuels are the largest producers of CO_2, the majority of research has focused around the capture of CO_2 from those sources. Also, industrial plants in general produce a much purer stream of CO_2 at much lower volumes which does not pose as big an engineering challenge to capture the CO_2. Where CO_2 is a contaminant in a commercial product stream such as natural gas or hydrogen, CO_2 capture becomes a necessity with the cost of capture being borne by the process.

3.2: Capture Parameters and Issues

A number of factors influence the choice of technology and the cost of capturing CO_2 and these vary depending upon the type of plant and the fuel used.

3.2.1: Quantity

Quantity refers to the actual mass or volume of pure CO_2 emitted to the atmosphere from the different kinds of sources mentioned earlier. This parameter has a special implication since the largest emitter (power plants burning fossil fuels) is not the easiest to capture due to the low concentration of CO_2 in the flue gas. However, economies of scale render this a viable option.

3.2.2: Quality

Quality is another important parameter to be considered while evaluating a source. Quality refers to the percentage of CO_2 in the flue gas and the overall composition of the flue gas itself. The quality of CO_2 emitted affects the capture costs in terms of technology used. For example, ammonia production is an industrial process that produces a nearly pure stream of CO_2 thereby eliminating most of the capture cost. Another major consideration within the quality parameter is the impurities present in the flue gas such as SO_2 and moisture which may have impacts on capture technologies employed.

3.2.3: Pressure

Generally speaking, the higher the pressure at which the flue gas is emitted, the lower are the capture costs. A higher pressure implies a lower volume and hence more options in terms of technology for capture. Also, since pipelines are the current most feasible option for large volume transportation of CO_2 and since pipeline transport requires compression of the CO_2 to above its critical pressure of 7.38 MPa – if the flue gas is emitted at pressures equal to or greater than this, no extra energy is expended in compressing the gas. This is very important since a significant portion of the total energy spent for separation and capture of CO_2 from a source is used for compression of the gas.

3.2.4: Retrofit Parameters

Given that power plants burning fossil fuels emit the majority of CO_2 into the atmosphere as compared to industrial sources, the main issue at the heart of technologies for the capture of CO_2 is the prospect of retrofitting existing plants with capture mechanisms versus building new plants specifically designed for CO_2 capture. This issue is especially significant given the fact that the average life expectancy of power plants burning fossil fuels is at least fifty years with a majority of the power plants in the US having more than half their expected lives remaining. Some of the major issues that arise while retrofitting existing plants as compared to new plants built with CO_2 capture as one of the process goals:

- Range of capture technology choices due to specific limitations of existing plants
- Age, smaller sizes, and lower efficiencies typical of existing plants
- Higher energy penalty (plant derating) for CO_2 capture due to less efficient heat integration for sorbent regeneration
- Existing plants not equipped with a flue gas desulfurization system for SO_2 control must be first retrofitted for high-efficiency sulfur capture to minimize contamination of the capture solvent by impurities in the flue gas such as SO_2
- Site-specific difficulties such as land availability, access to plant areas and need for special ductwork

A possible advantage for retrofits over new plants in the incremental cost for CO_2 capture is that in cases where the capital costs of the existing plant have been fully or partially amortized, the total COE of the plant with capture (including all new capital requirements) can be comparable to or lower than that of a new plant.

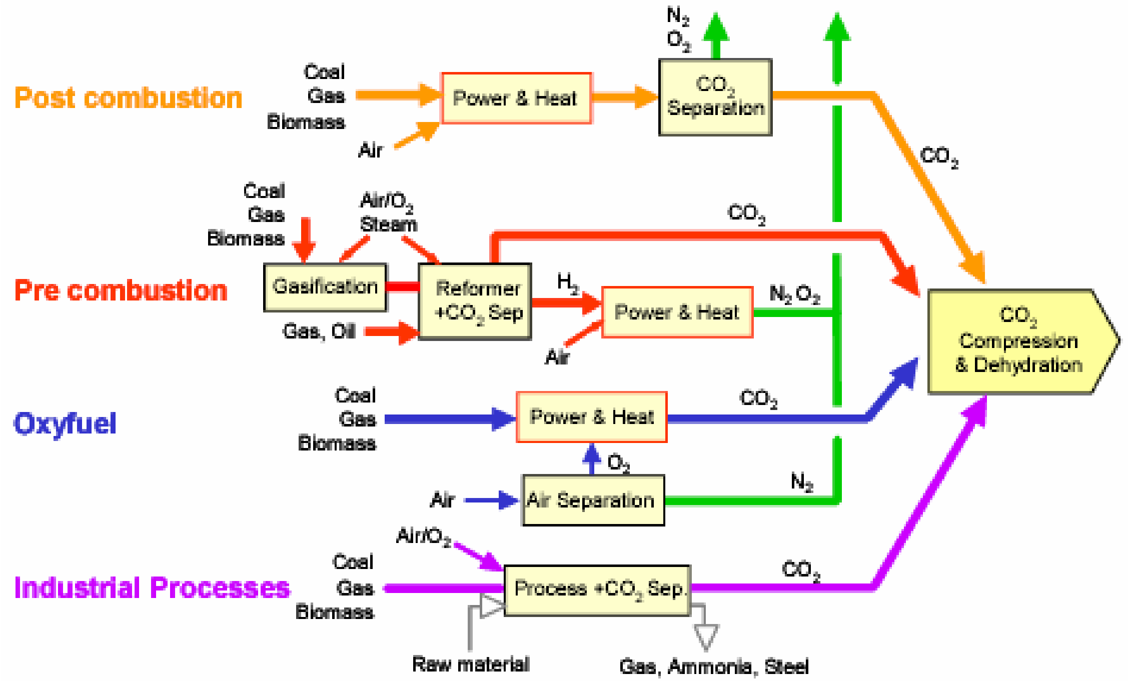

Figure 5: Different methodologies of CO_2 capture (courtesy BP America).

3.3: Methodologies for CO_2 Capture

Technology for separating CO_2 from gas streams was developed 60 years ago for use in gas processing. This has been adapted for use in power plants to separate CO_2 from flue gases – this configuration is known as post-combustion removal. Other configurations have also been identified as potentially attractive – pre-combustion removal and oxyfuel conversion. The different methodologies of CO_2 capture are presented in Figure 5 and discussed briefly below.

3.3.1: Post-Combustion Capture

Most of the world's electricity is currently generated from the combustion of fossil fuels, especially coal and (to an increasing extent) natural gas. Hence, the ability to capture and sequester the CO_2 emitted by such plants has been a major focus of CCS research. Capture of CO_2 from flue gases produced by combustion of fossil fuels and biomass is referred to as post-combustion capture. This is a downstream process, in which the CO_2 in flue gas at near atmospheric pressure is removed typically by a chemical absorption process. Because of the relatively low CO_2 concentration in power plant flue gases, chemical absorption systems have been the dominant technology of interest for post-combustion capture. For the most part, this study focuses primarily on post-combustion capture with all the sources mentioned in the following section falling under the purview of post-combustion capture.

3.3.2: Pre-Combustion Capture

The low concentration of CO_2 in post-combustion capture means that a large volume of gas has to be handled which results in large equipment sizes and high capital costs. A further disadvantage of the low CO_2 concentration is that powerful solvents have to be used to capture CO_2; also regeneration of the solvents, to release the CO_2, requires a large amount of energy. If the CO_2 concentration and pressure could be increased, the CO_2 capture equipment would be much smaller and different solvents could be used with lower energy penalties for regeneration. This can be achieved by pre-combustion capture. The fuel is reacted with oxygen or air and, in some cases, steam, to give mainly carbon monoxide and hydrogen and is commonly known as ‘syngas’. The carbon monoxide is reacted with steam in a catalytic reactor, called a shift converter, to give CO_2 and more hydrogen. The CO_2 is separated and the hydrogen is used as fuel in a gas turbine combined cycle plant. The process, in principle, is the same for coal, oil or natural gas but, when coal or oil are used, there are more stages of gas purification, to remove particles of ash, sulfur compounds and other minor impurities. The CO_2 emitted is at a high pressure and suitable for capture by physical solvents at low volumes and hence lower costs. Percentages of CO_2 captured are generally high.

3.3.3: OxyFuel Conversion[22]

The major component of any flue gas is nitrogen from the air feed. If there were no nitrogen, CO_2 capture from flue gas would be greatly simplified. In the oxyfuel approach, the power plant is fed oxygen produced by an air separation plant instead of air. The concentration of CO_2 in flue gas can be increased greatly by using concentrated oxygen instead of air for combustion, either in a boiler or gas turbine. The oxygen could be produced by, for example, cryogenic air separation which is already used on a large scale in the steel industry. If fuel is burnt in pure oxygen, the flame temperature is excessively high and so some CO_2-rich flue gas would have to be recycled to the combustor to make the flame temperature similar to that in a normal air-blown combustor. The advantage of oxygen-blown combustion is that once the moisture is removed, the flue gas has a CO_2 concentration of typically >90%, compared to 4-14% for air blown combustion, so only simple CO_2 purification is required. The disadvantage is that production of oxygen is expensive, both in terms of capital cost and energy consumption. Advances in oxygen production processes such as new and improved membranes that can operate at high temperatures could improve overall plant efficiency and economics. Oxyfuel combustion for power generation has so far only been demonstrated in small scale test rigs. Oxyfuel combustion may be an attractive option for retrofit of existing steam cycle power stations since the modifications that would need to be made at the power station would be relatively minor. Oxyfuel combustion could also be applied to gas turbines. However, gas turbines that use CO_2 as the working fluid would be substantially different to conventional gas turbines and a simple retrofit would not be feasible.

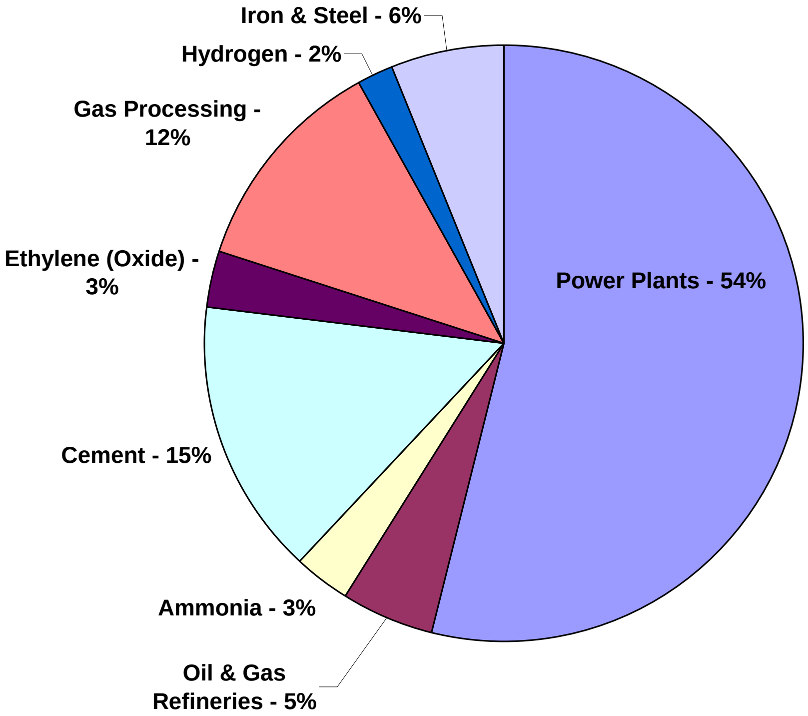

Figure 6: Distributions of different CO_2 emission sources by industry sector[23]

3.4: Types of Sources

This section describes the different sources of CO_2 that are mostly applicable to the post-combustion CO_2 capture methodology described in the previous section. As stated, the sources of CO_2 within this category can be classified into two broad classes of power plants burning fossil fuels and industrial sources. The relative distribution of CO_2 emissions by power plants (all types grouped together) and the major industrial sources is illustrated in Figure 6[23].

3.4.1: Power Plants Burning Fossil Fuels[24]

Pulverized Coal Plants (PC): These plants have been in use for upwards of 60 years and dominate the global market in terms of overall numbers and generating capacity. In operation, coal is burned in a boiler that raises high-pressure steam. This is then passed through a steam turbine and used to generate electricity. Over the years, many advances have been made with PC technology including environmentally focused measures to minimize emissions of SO_2, NO_X and particulates, as well as application of advanced steam cycles that allow for greater plant efficiency. Typical CO_2 content in the flue gas of PC plants is around 14%.

Integrated Gasification Combined Cycle (IGCC) Plants: In this type of plant, coal is reacted with steam and oxygen (or air) in a gasifier generating syngas. This gas is cleaned using different techniques and burned in a gas turbine. Since the CO_2 is captured prior to combustion, IGCC plants fall under the pre-combustion category described in the previous section. The concentration of CO_2 in the input to the cleaning stage can be in the range 15-60% (dry basis) and the total pressure is typically 30-60 atm. This means that a compact and low energy-intensive high pressure process such as physical absorption can be used for separation of CO_2. The exhaust heat is used to drive a steam cycle, producing additional electricity. Apart from coals, feedstocks such as oil refinery wastes are also used in these plants to generate electricity in an environmentally sound manner.

Natural Gas Combined Cycle (NGCC) Plants: Here, natural gas is combusted in a gas turbine to generate electricity. But the hot exhaust gases from the turbine are recovered and used to produce steam, which is used to drive a steam turbine, thus generating additional electricity. In this way, two cycles are combined, resulting in enhanced overall efficiency. With deregulation of the market for natural gas applications for power generation purposes, the number of NGCC plants has increased at a spectacular pace over the past 10 to 15 years. Capital costs for such plant are lower than those for coal-fired plants of equivalent generating capacity. Globally, NGCC technology now accounts for more than 50% of the market for new power generating capacity. Typical CO_2 content in the flue gas of NGCC plants is around 4%.

Oil-Fired Power Plants: Several main variants are used in the case of oil-fired power plants. Oil may be simply sprayed into a boiler furnace as a cloud of fine droplets, along with a supply of air, and burned. Steam is raised in a conventional steam cycle and used to power a steam turbine. Depending on the type of oil used and the plant configuration, overall thermal efficiency comes within the range of 23%-40%. Alternatively, as with gas-firing, oil can be used to fire a stand-alone combustion turbine, with no waste heat recovery. Again, as with gas, if waste heat is recovered, it can be used to raise steam to drive a steam turbine, thus forming a combined cycle and generating additional electricity. With the popularity of oil in the power sector consistently declining over the last decade, these kinds of power plants have been losing market share. Typical CO_2 content in the flue gas of oil-fired power plants is around 12%.

3.4.2: Industrial Sources

Natural Gas Processing Plants: In natural gas operations, CO_2 is generated as a by-product. Some natural gas reservoirs such as the one in Natuna gas field in the South China Sea contain over 70% CO_2 by volume[25]. In general, gas fields contain up to 20% by volume CO_2, most of which must be removed to produce pipeline quality gas at $< 2.5\%$ CO_2.[26] The first example of applying CO_2 capture technology to industrial processes such as natural gas processing is the Sleipner project in Norway.

Oil Refining and Petrochemical Plants: Gas-fired process heaters and steam boilers are responsible for the bulk of the CO_2 emitted from typical oil refineries and petrochemical plants. Although refineries and petrochemical plants emit large quantities of CO_2, they include multiple emission sources often dispersed over a large area. High purity CO_2 is currently vented to the atmosphere by some gas processing and petrochemical plants.

Steel Production[26]: The iron and steel industry is the largest energy consuming manufacturing sector in the world, accounting for 10-15% of total industrial energy consumption. Integrated steel mills are some of the world's largest emitters of CO_2. The CO_2 concentration in the flue gas of a steel plant is around 27%. Associated CO_2 emissions from the iron and steel industry in 1995 were estimated at 1,442 million tonnes.

Cement Production[26]: Emissions of CO_2 from the cement industry account for 15% of the total emissions of CO_2 from stationary sources. Cement production requires large quantities of fuel to drive the very high temperature and energy intensive reactions associated with the calcinations of the limestone and the clinker formation. CO_2 concentration in flue gases varies between 14-33% by volume.

Ammonia Production: Carbon dioxide is an inevitable by product of ammonia (NH_3) production. The amount of CO_2 produced during ammonia manufacturing in modern plants from natural gas is ≈1.26 tonne/tonne of ammonia. World ammonia production is more than 100 million tonnes/year indicating a capture potential of ≈ 126 million tonnes/year of CO_2. Since the CO_2 emitted is nearly pure, this presents a very low-cost opportunity to capture CO_2 from an industrial process. In fact, CO_2 produced by this process is widely used to supply the commercial market for CO_2.

3.5: Carbon Dioxide Capture Costs

This section presents a short summary of the possible ranges of costs for CO_2 capture from power plants and industrial processes. Since this investigation is more focused on integrating different areas of research together rather than developing fundamental research, the costs for CO_2 capture presented here draws heavily upon previous published research[27, 28, 29, 30, 31]. Because of the diversity of assumptions employed, a systematic comparison of cost results from different studies of CO_2 capture is not straightforward (or even possible in many cases). Nor are all studies equally credible, considering their vintage, data sources, level of detail, and extent of peer review. Thus, the approach adopted here is to rely as heavily as possible on recent peer-reviewed literature together with major publicly-available studies by governmental and private organizations involved in the CO_2 capture area.

Table 1 summarizes the range of current CO_2 capture costs for some of the major electric power and fuel systems mentioned in this chapter. These cost ranges reflect differences in the technical, economic and financial assumptions employed in different studies. Depending on the process or system in question, CO_2 capture (including CO_2 compression) adds anywhere from 20-85% to the production costs of a similar system without CO_2 capture. For power plants, the incremental costs are generally lowest for IGCC systems and highest for current coal combustion plants. In terms of total cost, combined cycle power plants fueled by natural gas typically produce the lowest-cost electricity, with or without CO_2 capture according to recent studies due to the lower carbon intensity of gas as compared to coal. These results, however, are especially sensitive to assumptions about gas prices and plant utilization factors.

Table 1: Summary of capture cost ranges estimated for certain power plants and industrial processes

Type of Source	**COST OF CO_2 AVOIDED (US$/t CO_2)**	
	Low	**High**
Old PC Plant	45	73
New PC Plant	42	55
New NGCC Plant	35	74
New IGCC Plant	13	37
New Hydrogen Plant	4	24
Iron and steel production	35	
Oil refining petrochemical	74	116
High purity industrial CO_2 sources	10	

3.6: Sources and the GIS

Point sources including power plants and industrial sources offer the most viable option for carbon capture because of the cost benefits from large scale capture as discussed earlier. Power plants generate large volumes of CO_2 while many industrial facilities generate high purity streams of CO_2. As a first step, there are certain essential characteristics of a source that need to have information available upon them. These include:

- Location

- Emissions by quantity
- Emissions by quality/proportion
- Pressure at which gases are emitted
- Plant type
- Fuel used
- Some index of 'retrofitability' for existing plants indicating the ease with which capture and separation equipment can be installed

There exist several databases for the United States with varying degrees of data populated with respect to the characteristics mentioned earlier. A couple of the major data sources that have been used to create the MIT GIS are described below.

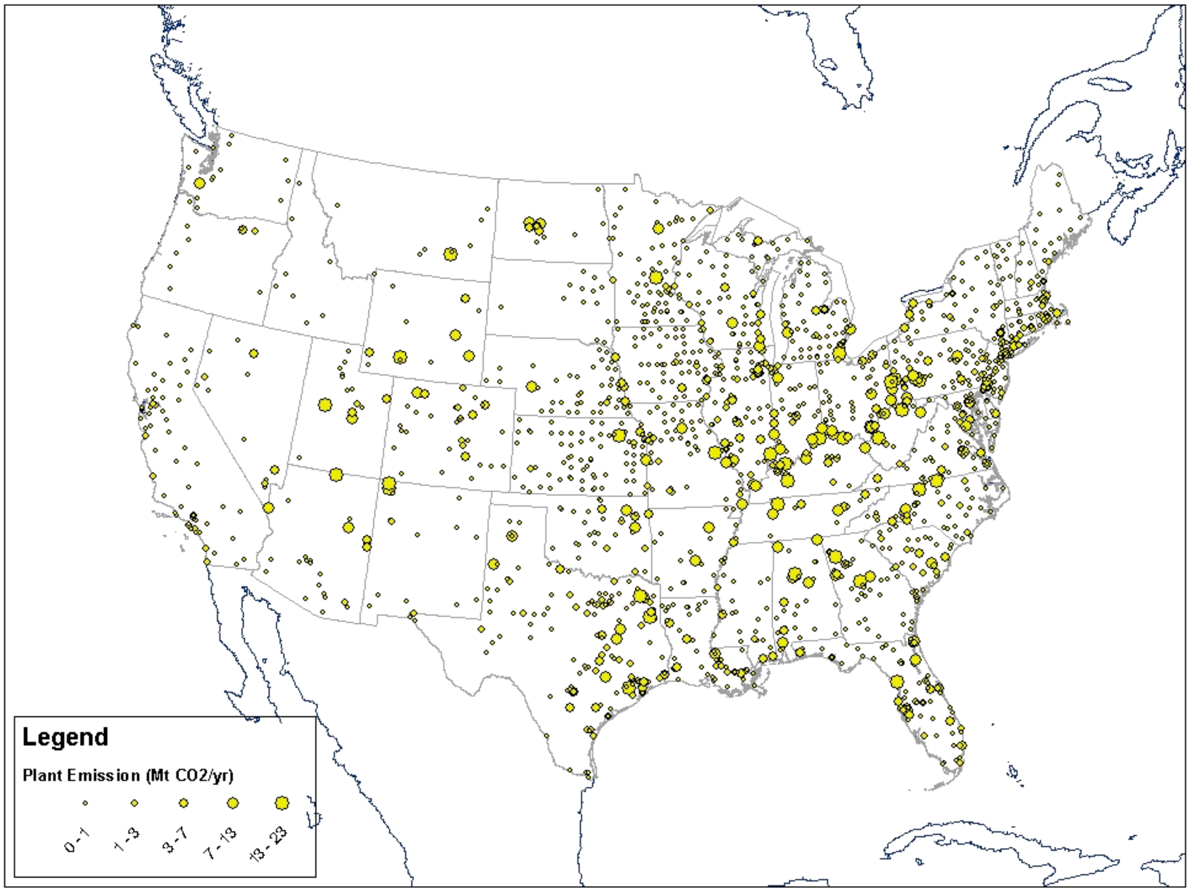

Figure 7: eGRID power plant locations scaled by quantity of CO_2 emitted in 1998

Emissions and Generation Resource Integrated Database (eGRID)[32]: The Environmental Protection Agency (EPA) initially released eGRID in 2000 and recently updated the database in 2002. eGRID integrates 24 data sources from the EPA, Energy Information Administration (EIA), and Federal Energy Regulatory Commission (FERC), some of which were confidential previous to the creation of eGRID. The database includes data on emissions (NO_x, SO_2, CO_2), generation (capacity, resource mix), ownership, and location for over 4,500 power plants in the US. This is the most comprehensive dataset on power plants in the US. A sample screenshot of the eGRID dataset is presented in Figure 7.

IEA PH4/9 Sources of CO_2[33]: Ecofys prepared a report on worldwide CO_2 sources for the International Energy Agency Greenhouse Gas R&D Program (IEA GHG). Ecofys provided MIT with an electronic version of the report entitled "PH4/9 Building cost curve for CO_2 Storage: Sources of CO_2" and the source data supporting the PH4/9 report (PH4/9). This study focuses "on the location and size of large anthropogenic CO_2 sources." The dataset characterizes facilities with 46 parameters for identification, location, CO_2 emissions, production, and fuels used.

As mentioned in the first chapter, a systems analysis is being conducted using the GIS to spatially representing different layers. The first of these layers would be the sources indicating the geographical location of each and accompanied by information on the different characteristics mentioned earlier in this section. As will be described in forthcoming chapters, layers representing reservoirs and transport options will be overlaid to produce a composite cost and options estimate of sequestration possibilities for any given source.

3.7: Summary

A summary of the key points described in this chapter is presented below in Table 2.

Table 2: Summary of key points of CO_2 capture

Sources

- Power plants burning fossil fuels
  - Pulverized coal (PC) plants
  - Integrated Gasification Combined Cycle (IGCC) Plants
  - Natural Gas Combined Cycle (NGCC) Plants
  - Oil-Fired Power Plants
- Industrial sources
  - Natural Gas Processing
  - Oil Refining and Petrochemical Plants
  - Steel Production
  - Cement Production
  - Ammonia Production

Methodologies

- Post-Combustion Capture
- Pre-Combustion Capture
- OxyFuel Conversion

Parameters/Aspects

- Quantity
- Quality
- Pressure
- Retrofit Parameters

Outputs for Systems Analysis

- Costs
- Volume/scale
- Quality

Level of Analysis

- Current: Estimation of capture costs by type of plant, very high level, several key assumptions made
- Future: More detailed cost analysis needed, depends on availability of more detailed data on existing plants in the context of retrofit parameters

4: CARBON DIOXIDE TRANSPORTATION

The next stage in the sequestration process after the capture of CO_2 is its transport to an identified reservoir. Of the three stages of carbon sequestration of capture/compression, transportation and storage, the area of transportation is the most developed. There is ample experience to draw upon from technological analogs in the form of natural gas and other gas pipelines that have been around for several decades. In addition, CO_2 itself has been transported in high pressure pipelines – there are about 3000 km of CO_2 pipelines in the world, mainly in North America, which have been transporting CO_2 since the early 1980s[34]. Another option for transportation of CO_2 over very long distances is tankers. Again, mature technological analogs exist in the form of tankers that have been used to transport LPG (liquefied petroleum gas) over very long distances.

From a systems analysis point of view, adding the cost of transportation to the cost of capture adds another layer in the GIS. The details of the manner in which the GIS calculates the cost of transportation will be discussed in greater depth in the chapter on matching of sources and reservoirs. However, at a higher level, an analysis on transportation uses a number of inputs to produce an output primarily in terms of cost of transport of CO_2 per unit mass.

4.1: Pipeline Transportation

This section draws heavily from a paper produced by the LFEE at MIT[35]. Over 110 million standard cubic meters (scm) per day of CO_2 are transported by pipeline in the United States, frequently for distances greater than 100 km. Transported CO_2 is most commonly used for EOR operations. The use of CO_2 for EOR is a proven technology with 72 CO_2

floods in the United States estimated in 2000[36]. This implies a fairly mature and stable technology for transportation of CO_2.

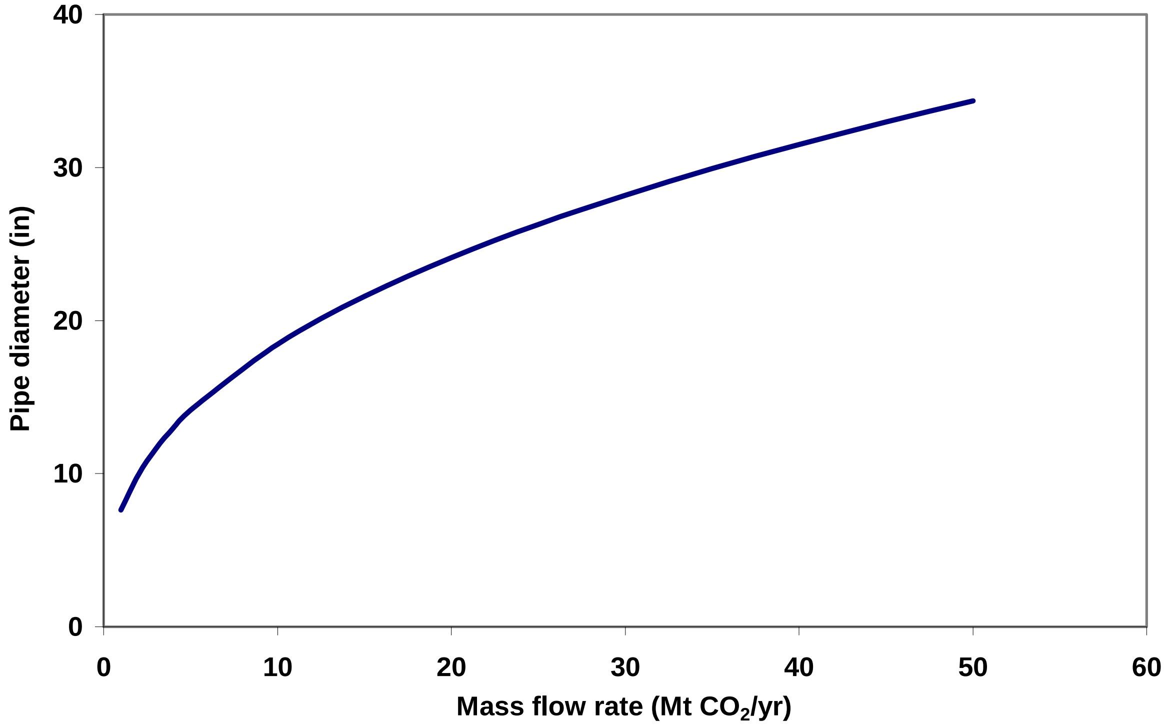

Figure 8: Diameter as a function of the CO_2 mass flow rate

4.1.1: Technical Parameters and Issues

Some of the factors that are considered in estimating the cost of pipeline transport are presented below. Sub-bullets indicate lower level parameters that are themselves functions of higher level parameters.

- Throughput
    - Pipe diameter
- Length
    - Number of booster compressors
    - Booster compressor inlet and outlet pressures

    - Whether an inlet compressor is required
- Onshore or offshore
- Type of terrain
- Country/region and the regulations applying
- Pipeline inlet pressure
- Quality of CO_2
    - Moisture
    - Impurities

As indicated, the pipe diameter is an important parameter and is actually a function of the throughput. The relationship between the required pipe diameter and the throughput is illustrated in Figure 8. This has some important implications in the fact that a pipe designed for a certain throughput may not be suitable for other levels of throughput and assumes importance when considering a network of pipelines from a localized region of sources to one reservoir.

Another important technical consideration in the design of pipelines for transport of supercritical CO_2 is that it should remain above its critical pressure of 7.38 MPa. This can be achieved by recompressing the CO_2 at certain points along the length of the pipeline. Recompression is often needed for pipelines over 150 km (90 miles) in length. It is important to note, however, that recompression may not be needed if a sufficient pipe diameter is used. For example, the Weyburn CO_2 pipeline runs for 330 km (205 miles) from North Dakota to Saskatchewan, Canada, without recompression[37].

An important factor affecting the cost of pipeline transportation is right-of-way (ROW) issues and existing ROW. A pipeline right-of-way is a strip of land over and around pipelines where some of the property owner's legal rights have been granted to a pipeline company. Right-of-way costs include obtaining the right-of-way and allowing for damages and this can significantly increase the capital expenditure for installing a pipeline. Conversely, existing ROW may prove certain pipeline paths more economical from a total cost viewpoint even though topographical considerations may not necessarily indicate that to be the cheapest option.

A survey of North American pipeline project costs yields several pertinent observations. First, for a given pipeline diameter, the per unit distance cost of construction is generally lower the longer the pipeline. Second, pipelines built nearer populated areas tend to be more expensive. Finally, road, highway, river, or channel crossings and marshy or rocky terrain also greatly increase the cost[38].

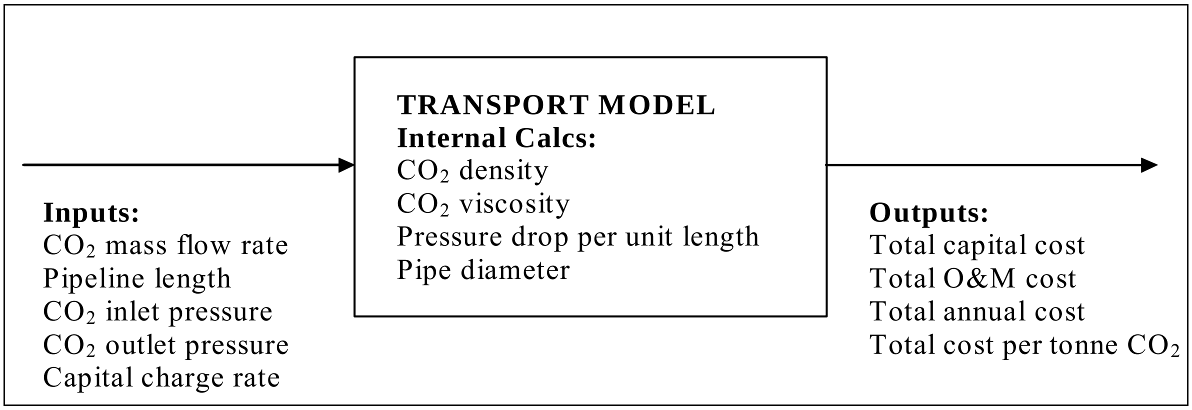

Figure 9: Pipeline transport cost model overview diagram

As mentioned earlier, from a systems analysis viewpoint, there are certain key inputs that go into the analysis to produce the outputs. This inputs, outputs and internal calculations are illustrated graphically in Figure 9.

4.1.2: Costs

The amount of cost data on CO_2 pipelines in the open literature is very limited, but there is an abundance of cost data for natural gas pipelines. For this reason, land construction cost data for natural gas pipelines were used to estimate construction costs for CO_2 pipelines. This is adequate given that there is little difference between land construction costs for these two types of pipeline.

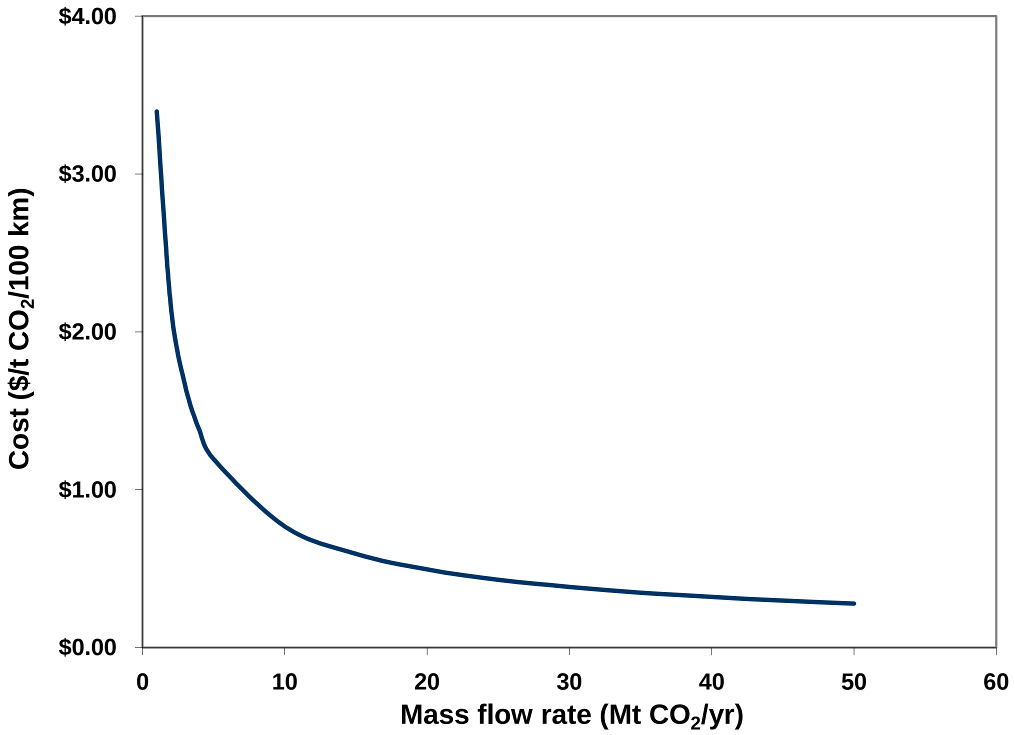

Figure 10: Cost of CO_2 transport as a function of the CO_2 mass flow rate

A regression analysis between the average cost ($/mile) and the pipeline diameter (inches) for natural gas pipelines yields total pipeline construction costs at $20,989/in/km. Applying an O&M (operation and maintenance) cost factor of $3,100/km gives the corresponding total O&M costs. Finally, the total annual cost per tonne of CO_2 is found by annualizing the construction cost using a capital charge rate of 15 percent per year and adding this to the annual O&M cost. Figure 10 shows the cost of CO_2 transport as a function of CO_2 mass flow rate. Significant economies of scale in the unit cost of transport are observed as the mass flow initially increases but the cost starts to level out beyond 20 Mt/year of CO_2 transported.

4.2: Pipeline Transportation and the MIT GIS

Several datasets have been included in the MIT GIS to provide information on the different parameters determining the cost of CO_2 transportation by pipelines. In conjunction, this information not only facilitates the cost estimation of transporting CO_2 between two given points over a certain route but also helps determine the 'least-cost' path for transportation. A list of the different databases used in the GIS follows.

Electronic Topography, 5 Minute Gridded Elevation Data (ETOPO5)[39]: Land and sea-floor elevations on a 5-minute latitude/longitude grid

States and Counties[40]: Map layers portraying year 2000 state and county boundaries of the United States.

U.S. Census Database, 2000[41]: Year 2000 population information for the United States and Puerto Rico from the U.S. Census Bureau.

U.S. Streams and Water Bodies[42]: Streams and water bodies of the United States

U.S. Railways[43]***:*** Railroads in the United States

U.S. Roads[44]***:*** Major roads in the United States

Land Use and Land Cover (LULC)[45]: Data consists of historical land use and land cover classification data that was based primarily on the manual interpretation of 1970's and 1980's aerial photography. Secondary sources included land use maps and surveys. Along with the LULC files, associated maps are included which provide additional information on political units, hydrologic units, census county subdivisions, and Federal and State land ownership.

4.2.1: Cost Calculation in the GIS

Using the generic costs for pipelines and the different datasets discussed in previous sections, the GIS can be utilized to output pipeline transportation costs at different levels.

The GIS works on the concept of ‘cells’. Any geographical area can be considered as a grid of perpendicular intersecting lines forming squares and the smallest unit on a grid is called a cell. The dimension of a cell is dependent on user input and was 30 m for this investigation.

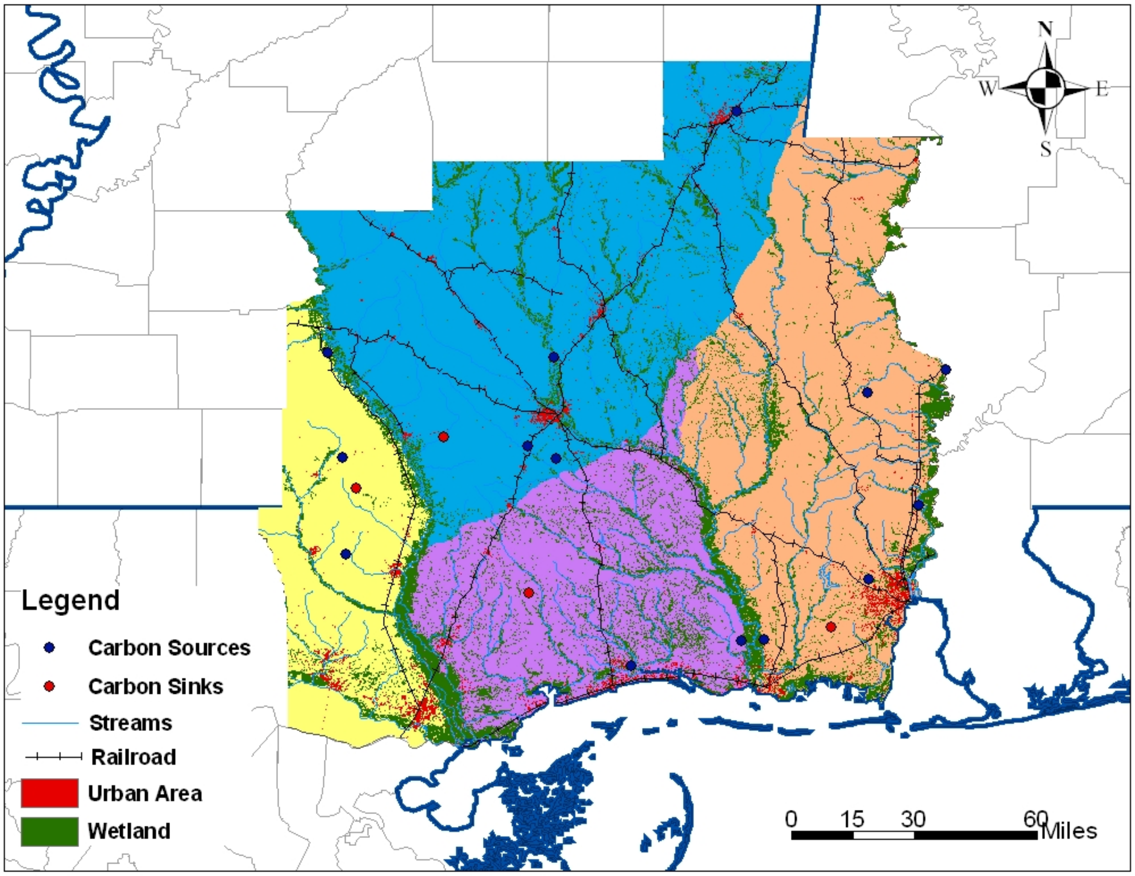

Figure 11: Minimized cost region for different reservoirs

The first level of analysis is based on a shortest-path algorithm that basically yields a straight line path between a CO_2 source and a matching reservoir. The output purely based on the straight line distance between the source and the reservoir without taking into account any other factors such as topography, water bodies, protected areas, urban areas etc.

The next level of analysis is based on a least-cost-path algorithm rather than on the shortest distance as illustrated in Figure 11. This means that in addition to distance, the resulting path of a pipeline between a CO_2 source and a reservoir is based on factors such as topography, water bodies, protected areas, urban areas etc. The alphabets represent reservoirs and numbers represent different sources in the figure. A careful observation of the illustration reveals the existing topographical details of the region such as rivers/streams, wetlands, urban areas amongst others. The GIS considers all these details and calculates for every given reservoir an area of minimum transportation cost around it such that for every CO_2 source within this area, the cost of pipeline transportation of the CO_2 is the least for that given reservoir. It is interesting to note that the boundaries of any given region largely coincide with natural boundaries such as wetlands. This is because the calculated cost in the GIS for crossing a wetland is extremely high. The illustration presents this with the different colored regions representing the minimum cost regions for the reservoirs contained within them.

The next level of analysis would take into account the ROW and existing ROW considerations in addition to all the other factors mentioned above. This is part of the future work planned to be done in the MIT GIS.

4.3: Summary

To summarize the key points presented in this chapter, of the three stages of carbon sequestration as defined by the IEA as capture, transportation and storage, the area of transportation is the most developed and mature. Hence, a very in-depth analysis of transportation costs and issues can be conducted to contribute to the overall goal of systems analysis. A summary table is presented in Table 3.

Table 3: Summary of key points of CO_2 transportation

Modes

- Pipeline transport

Parameters/Aspects

- Throughput
    - Pipe diameter
- Length
    - Number of booster compressors
    - Booster compressor inlet and outlet pressures
    - Whether an inlet compressor is required
- Onshore or offshore
- Type of terrain
- Country/region and the regulations applying
- Pipeline inlet pressure
- Quality of CO_2
    - Moisture
    - Impurities

Outputs for Systems Analysis

- Costs
- Capacities

Level of Analysis

- Current
    - Straight line path
    - Least cost path not including ROW
- Future:
    - Least cost path incorporating ROW factors

5: CARBON DIOXIDE STORAGE RESERVOIRS

As mentioned in the second chapter, the third stage in the sequestration process involves the injection of the CO_2 into identified reservoirs based on a set of considerations. Once again, this investigation considers geological formations only to serve as CO_2 reservoirs.

There are certain key considerations that influence the choice of storage:

- The potential storage period for the chosen reservoir should extend from hundreds to thousands of years
- The capacity of the reservoir should be adequate to handle the CO_2 emitted from identified sources
- The storage site should be selected such that the injectivity cost of CO_2 is minimized
- The environmental impact should be within statutory regulations and in general as low as possible

Geologic formations that are currently considered to hold potential for CO_2 storage include:

- Saline formations
- Oil and gas wells
    - Depleted oil and gas wells
    - Non-depleted oil and gas reservoirs for Enhanced Oil Recovery (EOR)
- Coal seams
    - Unmineable coal seams
    - Coal seams amenable to Enhanced Coalbed Methane Recovery (ECBMR)

Each of these reservoirs will be discussed in greater detail in following sections but a quick summary of the estimated potential storage capacity of each of the different categories of reservoirs is presented Table 4. The worldwide production of CO_2 and current utilization of all possible storage reservoirs are also presented for reference.

Table 4: Global capacity of potential geologic storage reservoirs[22]

Sequestration option	Worldwide capacity (Gt C)
Deep saline formations	100–10,000
Depleted oil and gas reservoirs	100–1000
Coal seams	10–1000
Worldwide production of CO_2 ≈ 20 Gt C/yr	
Utilization: Currently < 0.1 Gt C/yr	

From a systems analysis point of view, the inputs for evaluating a given reservoir would be values for the different important parameters defined in the next section. The outputs from the analysis would be the costs for storage with associated capacity, risk and containment potential from a high level perspective.

5.1: Reservoir Parameters[46]

Various CO_2 physical properties and other criteria play a role in the selection of the appropriate means and sites for CO_2 storage in geological media. At normal atmospheric conditions, CO_2 is a thermodynamically very stable gas heavier than air. For temperatures greater than 31°C and pressures greater than the critical point of 7.38 MPa (74 bar), CO_2 is in a supercritical state. At these pressure and temperature conditions, CO_2 behaves still like a gas by filling all the available volume, but has a 'liquid' density that increases, depending on pressure and temperature, from 200 to 900 kg/m^3, thus approaching water density[47,48]. CO_2 is soluble in water; its solubility increases with pressure and decreases with temperature and water salinity. CO_2 in a supercritical state is immiscible in water. At low temperatures and elevated pressures, CO_2 forms a solid hydrate heavier than water. Another important property of CO_2 is its affinity to coal over methane – coal selectively releases methane (if present) and adsorbs CO_2. All these properties of CO_2 and various other criteria play a role in the selection of appropriate methods and sites for CO_2 disposal and sequestration in geological media. Depending on reservoir temperature and original pressure, CO_2 can be stored either as a compressed gas, liquid or in the supercritical phase. Based on these factors, the critical parameters influencing the choice of a storage reservoir can be summarized as:

5.1.1: Depth

Previous studies have assumed implicitly that the pressure distribution in a sedimentary basin is hydrostatic increasing linearly with depth at a rate of 1 MPa per 100 m. With this assumption and for average geothermal gradients of 25°C /km, it has been determined that the conditions for a CO_2 supercritical state would be roughly met for depths greater than 800 m. Since then, this depth of 800 m has been generally accepted as the base case threshold for CO_2 injection in a supercritical state for a first attempt at systems analysis.

5.1.2: Capacity

The capacity of a potential CO_2 reservoir is one of the most important factors governing the choice of any reservoir. Given the large capital cost of installing CO_2 storage equipment and more importantly, transportation pipelines from sources to assigned reservoirs, a reservoir proves economical only if it has the capacity to store the CO_2 from those sources for a significantly long period of time of the order of several decades if not more. Also, the possibility of future addition of sources to a reservoir already being used for CO_2 storage would make larger demands on capacity and underlines the need for selecting a reservoir with a high storage capacity. The two major factors that affect the capacity of a reservoir are listed below.

- ***Porosity:*** Porosity evaluation is needed to estimate the potential volume or capacity available for CO_2 sequestration in a reservoir. Available volumes for CO_2 sequestration can then be converted into tonnes of sequestered CO_2 based on the relation between in-situ temperature and pressure and CO_2 density as mentioned earlier.
- ***Reservoir Contact Efficiency:*** Besides porosity, there is another factor called the 'reservoir contact efficiency' that determines the storage capacity of a reservoir. This refers to the effective percentage of available pore space that the CO_2 ultimately ends up occupying and typically ranges between 20% and 40% with average values around 33%[49]. This occurs due to the processes of gravity segregation and viscous fingering arising from the low density and viscosity of CO_2 relative to the surrounding media. The lower density coupled with the low viscosity makes the CO_2 buoyant and tends to channel towards the top of the reservoir thereby not occupying all the available pore space. This phenomenon is generally observed in sequestration in saline formations and EOR operations.

5.1.3: Injectivity[50]

An important step in the analysis of the potential of a geologic reservoir for CO_2 sequestration is identification of permeable zones for CO_2 injection. This involves the estimation of the injectivity of the reservoir. It is important since the injectivity of a reservoir determines the number of injection wells required which directly affects the cost of CO_2

storage in the reservoir. A relationship, derived by Law and Bachu is used to determine CO_2 injectivity from CO_2 mobility. The equation for CO_2 injectivity is

$$CO_2\ injectivity = 0.0208 \times CO_2\ mobility$$

where CO_2 injectivity is equal to the mass flow rate of CO_2 that can be injected per unit of reservoir thickness and per unit of downhole pressure difference, and CO_2 mobility equals the CO_2 absolute permeability divided by CO_2 viscosity.

Major parameters affecting injectivity of a reservoir are described briefly below.

- ***Permeability:*** Rock permeability is a critical factor in establishing CO_2 injection rate and ultimate volume. Injection in highly permeable zones is preferred because the pressure buildup will be accordingly low, avoiding the risk of fracturing which could open conduits for upward CO_2 migration and possible escape. Identification of permeable zones is necessary for CO_2 injection and storage in coal beds and in deep saline formations. Oil and gas reservoirs, unless in tight rocks, have already enough permeability that allows hydrocarbon production and therefore CO_2 injection.
- ***Pressure:*** In order to achieve large storage capacities underground, CO_2 should be stored above supercritical pressure (supercritical point at 31°C, 7.38 MPa/74 bar) and deeper than 800 meters below the surface. The higher the pressure in the reservoir, the denser is the CO_2 stored in it occupying a lower volume. However, higher reservoir pressures affect injectivity adversely and therefore increase storage costs.
- ***Thickness:*** The thickness is a parameter in the calculation of the injectivity of the reservoir. In general, a thicker reservoir has better injectivity than a thinner one.

5.1.4: Reservoir Containment/Integrity

This is one the most important factors to consider while selecting a storage option. It is also an area where little or no information is readily available. Estimation of containment potential is important as it is the basic premise on which CCS efforts have developed. Lack of proper containment of stored CO_2 and its subsequent release back to the atmosphere would defeat the basic goal of sequestration. Even if the sequestered CO_2 is not released into the atmosphere, lack of adequate containment could witness the release of the CO_2 into adjacent resources such as fresh groundwater creating new environmental challenges. Some of the factors to be considered while choosing a geologic storage site include basin hydrodynamics, flow driving mechanisms, natural geologic barriers, cap rock, tectonic settings, seismic activity potential amongst others.

5.2: Types of Reservoirs

5.2.1: Oil and Gas Reservoirs

Though a relatively new idea in the context of climate change mitigation, injecting CO_2 into depleted oil and gas fields has been practiced for many years. It has been or is being currently used worldwide in more than 70 tertiary enhanced oil recovery (EOR) operations to increase oil mobility and to displace up to 40% of the residual oil left in an active reservoir after primary production and water flooding.

Depleted oil and gas reservoirs display particular promise in this regard. These reservoirs in structural and stratigraphic traps have demonstrated good storage and sealing characteristics over geological time and they can thus be used for CO_2 sequestration once a reservoir is no longer exploited (depleted). The term ‘depleted’ is an economic term and relative for oil reservoirs as there is always residual oil in place that may be recovered in the future depending on technological advances and economic conditions. For gas reservoirs, this problem does not exist, so they are better candidates for CO_2 sequestration. The trapping mechanism (structural, stratigraphic or lithologic) that retained hydrocarbons in the first place will ensure that CO_2 does not reach the surface. The proven trap, known reservoir properties and existing infrastructure make storage of CO_2 in depleted hydrocarbon reservoirs a simpler and cheaper option than other forms of CO_2 sequestration. Closed depleted gas reservoirs represent the most straightforward case, as primary recovery usually removes as much as 95% of the original gas in place, and CO_2 can be used to re-pressurize the reservoir to its original pressure. Most oil and gas reservoirs are not located near primary sources of CO_2 production, so new pipelines will be needed to connect the CO_2 sources with suitable sequestration sites.

5.2.2: Unmineable Coal Seams

An important property of CO_2 is its affinity to coal over methane – coal selectively releases methane (if present) and adsorbs CO_2. Injecting CO_2 into coal beds that are too deep or uneconomic for coal mining presents a twofold advantage. First, CO_2 is sequestered by adsorption on the coal matrix. Second, methane may be produced as a byproduct which although itself a greenhouse gas, can be used instead of coal as a much cleaner fuel implicitly reducing CO_2 emissions. Carbon dioxide injection into coal beds is already used in the San Juan basin to enhance methane recovery (ECBMR: enhanced coalbed methane recovery) by increasing the pressure drive and decreasing the amount of produced water that has to be disposed of by injection back into deep formation. The bulk of coalbed methane resources occur in China, Russia, India, central and Eastern Europe, Australia, USA and Canada, all countries basically with large coal deposits. However, most coal seams have unfavorably low permeability because of their complex geological setting, such as in Western Europe and in China. Thus, depending on geological conditions, CO_2 sequestration in coal beds has potential for the mid to long term storage.

5.2.3: Saline Formations

The pore and fracture space in the Earth's crust is filled with water. Deep formations contain highly saline water that is not fit for industrial and agricultural use or for human consumption. Such formations are already used for injection of hazardous and non-hazardous liquid waste. The high pressures encountered in deep formations indicate that they can withstand CO_2 injection. Some of the injected CO_2 (up to 29%) will dissolve in the water and the rest will form a plume that will ride at the top of the formation. While the dissolved CO_2 will travel with the velocity of the formation waters (of the order of cm/year), the CO_2 plume will be driven both by the natural hydrodynamic flow and by its buoyancy with respect to water. CO_2 can be hydrodynamically sequestered in deep formations for long periods of time. This is because of the slow spreading from the injection well and hydrodynamic dispersion in the formation once outside the well radius of influence and of extremely long residence time due to the very low velocity of formation waters (less than 0.1 m/year). Also, similar to utilization in EOR operations and sequestration in depleted hydrocarbon reservoirs, the technology is already developed and easy and economic to apply. Thus, deep saline formations have, by far, the largest potential for CO_2 sequestration in geological media in terms of volume, duration, economics and minimum environmental impact. A commercial scheme for CO_2 sequestration in an offshore North Sea formation is already in place in Norway where 106 tonnes of CO_2 are extracted annually from the Sleipner field and injected into the 250 m thick Utsira formation at a depth of 800 m below the sea bed.

5.3: Costs

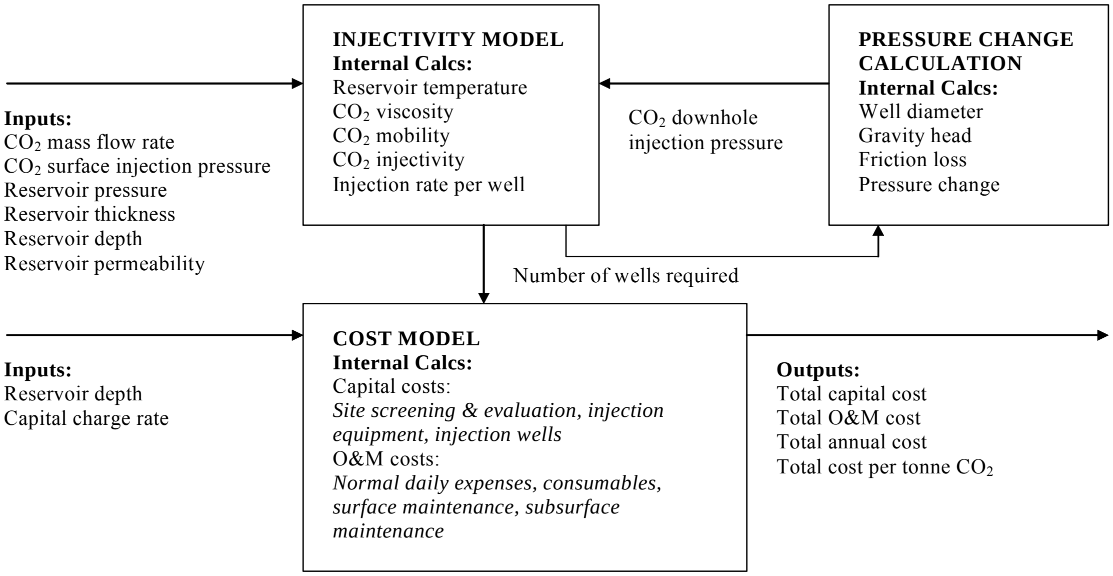

Figure 12: Geologic storage cost model overview diagram[35]

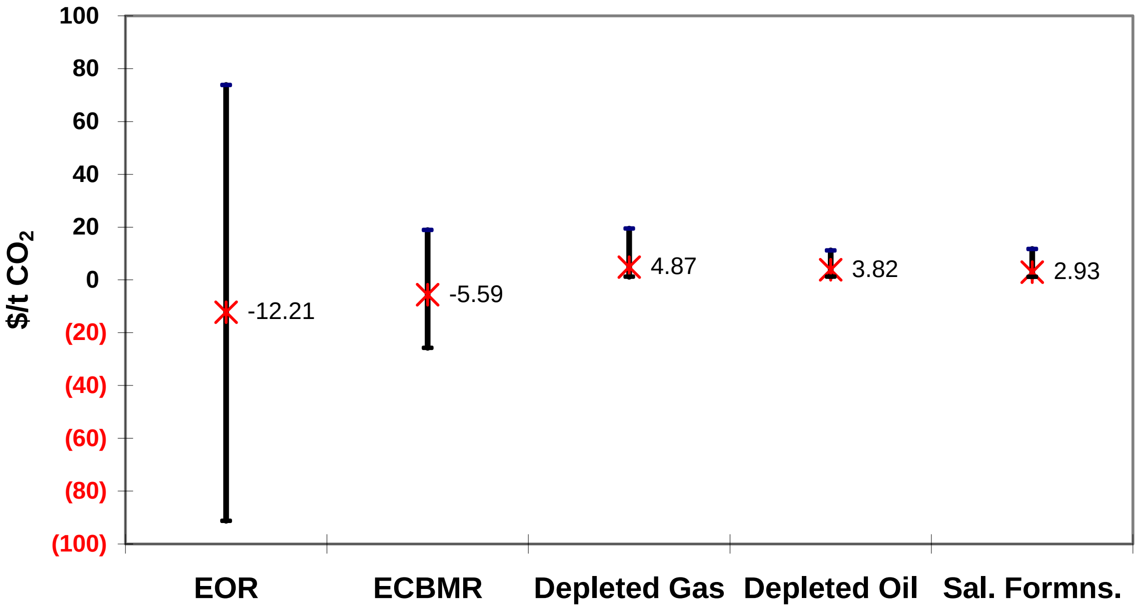

Figure 13: Costs ranges for CO_2 storage options on a GHG-avoided basis.

The cost model for the geologic CO_2 storage options can be broken down into a number of components. First, there is a relationship for calculating the number of wells required for a given CO_2 flow rate, CO_2 downhole injection pressure, and set of reservoir parameters. Second, an iterative procedure is used to take into account the interdependent relationship between CO_2 downhole injection pressure and the number of wells. Third, a set of capital and O&M cost factors are used to determine cost based on the number of wells required. Each of these components is illustrated in the overview diagram in Figure 12.

The storage costs for different kinds of reservoirs are drawn from a paper published by the LFEE at MIT[35]. Figure 13 summarizes the costs of the various carbon storage technologies on a greenhouse gas-avoided basis. The points on the graphs are for a typical base case, and the bars represent the range between representative high- and low-cost cases. The ranges reflect the range of conditions found in the various reservoirs (depth, permeability, etc.), the distance between source and reservoir (a range of 0–300 km here), and the by-product prices (i.e., oil and gas).

5.4: Reservoirs and the GIS

As was mentioned earlier in this chapter, three broad categories of reservoirs were identified and have been incorporated into the GIS include deep saline formations, oil and gas wells and coal seams. Since technology in this arena is still developing, different data chroniclers included information about parameters they thought were important to the science of CCS. Also, databases identified for this study were not necessarily initially developed for CCS studies and so were developed with a different set of characteristics deemed important for the purpose they were being developed. A description of some of the major databases follows.

5.4.1: Brine Formation Database[51]

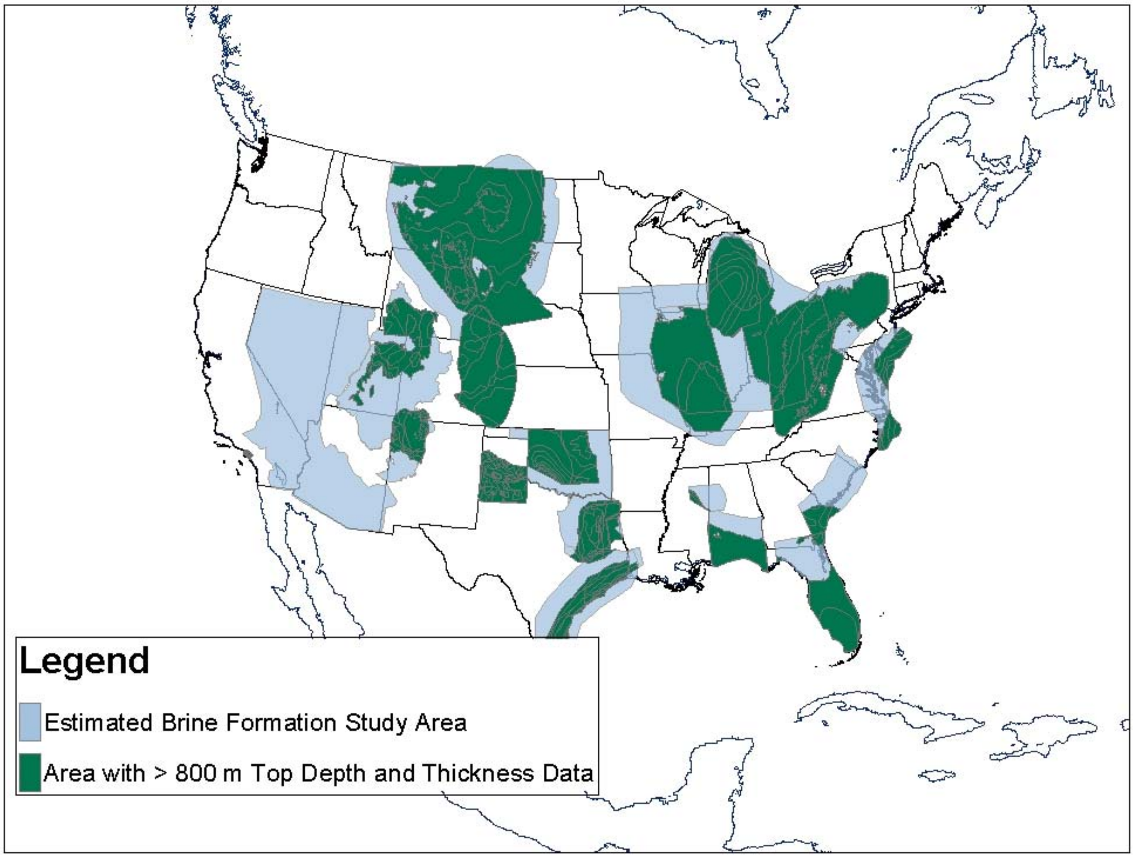

Figure 14: UT BEG's brine formations with depth and thickness data

The Bureau of Economic Geology at the University of Texas at Austin (UT-BEG) developed the *Brine-Formation Database* under a grant from the Department of Energy National Energy Technology Laboratory (DOE-NETL) in 2000[51]. UT-BEG designed the database to be GIS compatible and included power plant locations to match CO_2 emitters with brine formations. Figure 14 presents a GIS screen shot of the different brine formations in this database. UT-BEG selected 21 brine formations based on specific parameters that limited the scope of their exploration. The parameters, as listed in the documentation, were:

- Geographic distribution of CO_2 sources;
- Appropriate depth, injectivity, and seal;

- Adequate information to characterize the target; and
- Diverse geologic properties of the pool of selected formations.

5.4.2: Gas Information System

Energy and Environmental Analysis, Inc (EEA) developed the Gas Information System (GASIS) under contract with NETL between 1993 and 2000. The GASIS project was intended to provide a national database of gas reservoir properties and recovery data to aid natural gas producers in field development and exploration. EEA merged data from the Department of Energy and Gas Research Institute's Gas Atlas data sets, Dwight's databases, and other public data sources. Figure 15 shows the onshore coverage of the GASIS data.

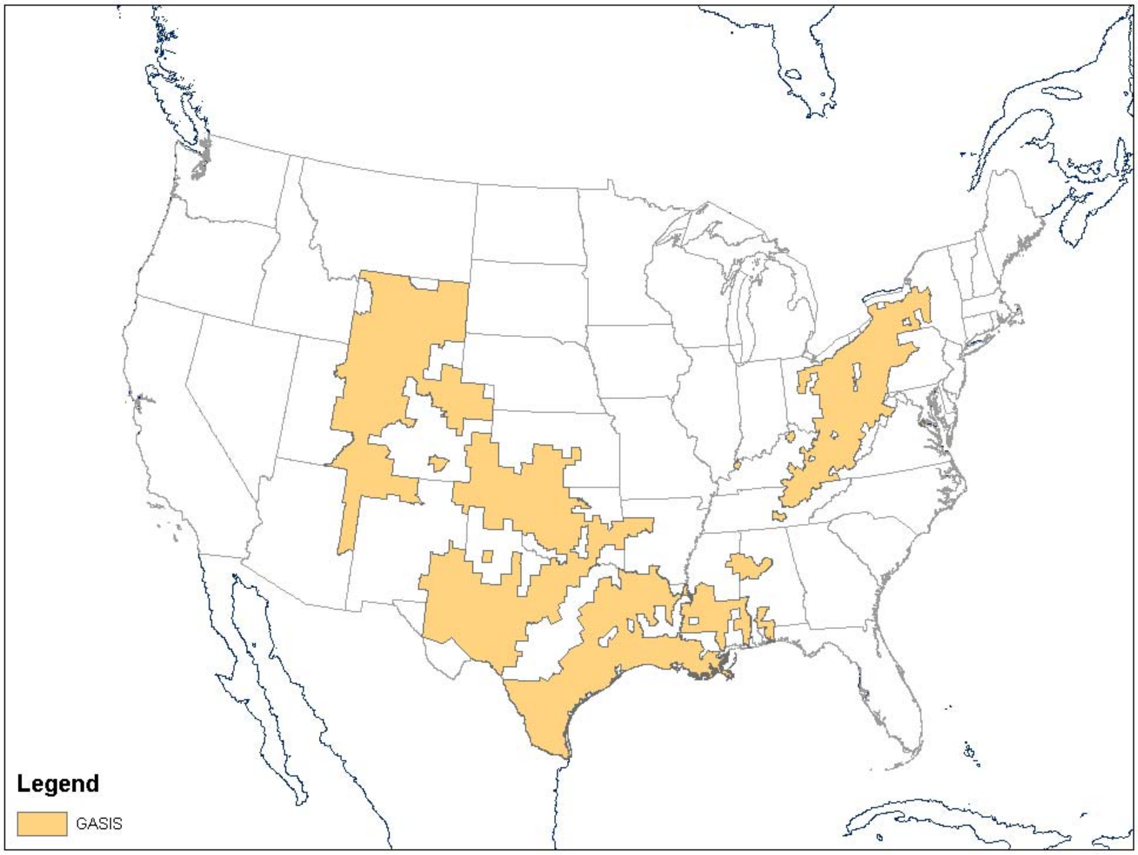

Figure 15: Onshore areas with reservoir data in GASIS

5.4.3: Coal Fields of the United States

The primary dataset used in MIT's GIS for coal reservoirs is the "Coal Fields of the United States" published by the United States Geological Survey (USGS). This dataset is the most complete and useful for analyzing potential reservoirs for CO_2 storage in coal fields in the United States. It is a polygon coverage representing all coal fields in the US as shown in Figure 16. Most of the material for the conterminous United States was collected from James Trumbull's "Coal Fields of the United States, Conterminous United States" map (sheet 1, 1960). The Gulf Coast region was updated using generalized, coal-bearing geology obtained from State geologic maps[52].

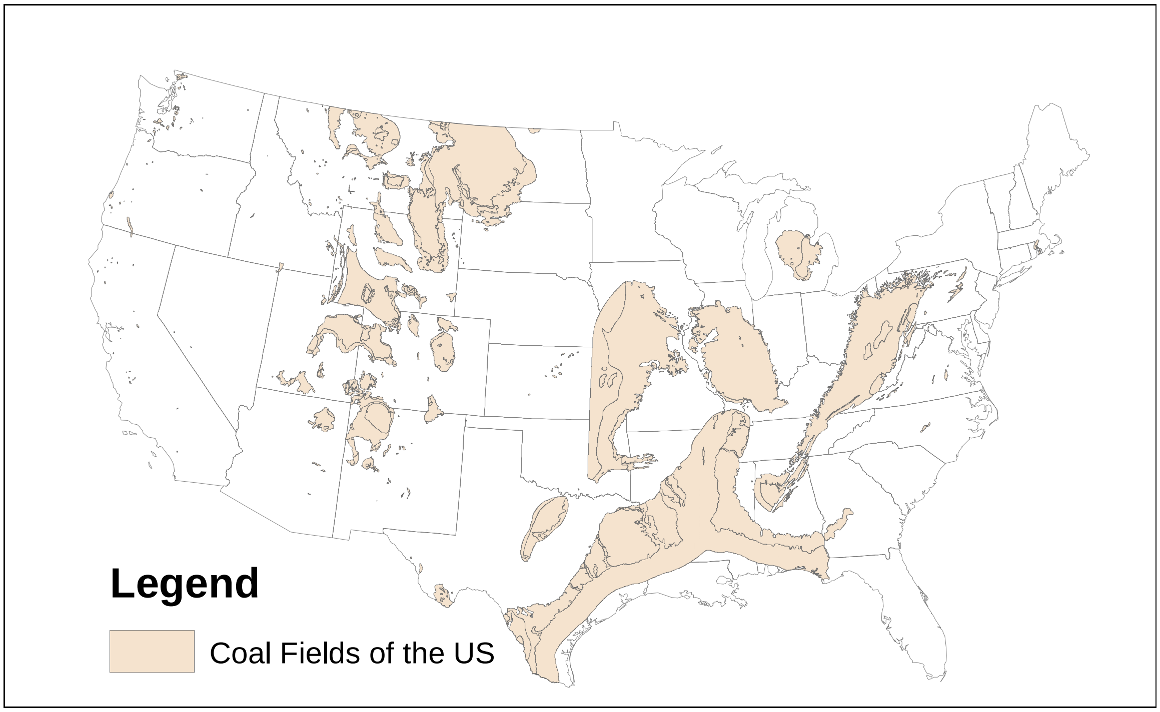

Figure 16: Coal fields of the United States

While this dataset provides useful information for a broad overview of US CO_2 storage options, it does not contain enough information for evaluating and selecting individual project sites. The data resolution is not high enough (resolution is 1:5,000,000), nor is there enough data on requisite parameters such as porosity, permeability, and other information needed to make confident planning decisions.

5.5: Summary

A summary of the key points described in this chapter is presented below in Table 5.

Table 5: Summary of key points of CO_2 storage

Reservoirs

- Saline formations
- Oil and gas wells
  - Depleted
  - Non-depleted for Enhanced Oil Recovery (EOR)
- Coal seams
  - Unmineable coal seams
  - Other coal seams amenable to Enhanced Coalbed Methane Recovery (ECBMR)

Parameters/Aspects

- Depth
- Capacity
  - Porosity
  - Reservoir contact efficiency
- Injectivity
  - Permeability
  - Pressure
  - Thickness
- Containment
  - Basin hydrodynamics
  - Flow driving mechanisms
  - Natural geologic barriers
  - Cap rock
  - Tectonic settings
  - Seismic activity potential

Outputs for Systems Analysis

- Costs
- Capacities
- Reservoir Containment/Integrity

Level of Analysis

- Desired – calculations based on actual data
- Alternate 1 – Extrapolate "play" data
- Alternate 2 – Use estimated or default data

6: SYSTEM EVOLUTION AND SAMPLE CASE STUDY

The actual evolution of the systems methodology for evaluating sequestration options is presented in this chapter. A Decision Support System (DSS) is developed using the Object-Process CASE (OPCAT) tool to model the complex and interdisciplinary system. This chapter integrates all the major steps outlined in the previous chapters in a sample problem. This is to illustrate the methodology of evaluating CCS options for a given set of sources. A region located mostly in the state of Mississippi and covering parts of Alabama and Louisiana in the US was identified for this model case study. The methodology will be applied at a later time to evaluate CCS potential in the South East Regional Carbon Sequestration Partnership (SERCSP) and the West Coast Regional Carbon Sequestration Partnership (WCRCSP).

6.1: OPCAT

Before describing the DSS, a short overview of OPCAT is helpful in understanding the tool itself and the kinds of flexibility it allows in building a DSS. OPCAT is a tool for implementing Object Process Methodology or OPM, a modeling process developed by Dov Dori, a joint professor at the Technion, Israel and MIT[53]. Simply described, OPM develops models that are a combination of structural models and information flow models such as flowcharts. The specific nuances of OPM include:

- A comprehensive systems modeling, engineering, and lifecycle support paradigm
- Two major features:
    - Unification of function, structure and behavior in a single model
    - Bi-modal expression of the model via intuitive yet formal graphics and equivalent natural language

The motivation behind the development of OPM can be summarized as:

- Need for modeling complex and interdisciplinary systems
- Need for a universal modeling, engineering, and lifecycle support approach
- Need for a simple, formal, generic paradigm for systems development.

The OPM ontology consists of two basic building blocks – entities and links. These can be further sub-divided as:

- Entity types:
    - **Object:** A thing that exists for some time
    - **State:** A situation at which an object can be
    - **Process:** A thing that transforms an object
- Link types:
    - **Structural link:** A link denoting a persistent relation between objects
    - **Procedural link:** A link between a process and the object it transforms or a state of that object

All the features described above have been utilized in building the DSS.

6.2: Decision Support System Model

The DSS has a required number of inputs or equivalent assumptions that are fed into the model. There are also certain conditions or constraints that are imposed on the model so that the outputs are within defined limits. Given the inputs and the constraints, the model performs internal calculations on the information to produce certain outputs. The sequence of steps from inputs to outputs is outlined below.

6.2.1: Inputs

The different inputs that go into the DSS include:

Location: This input defines the general area of interest for selected sources of CO_2. it can range from a simple longitude-latitude coordinate reference for a single point source to a number of sources within a defined geographical location known as a 'polygon' in GIS terminology and referred to henceforth as such. While not necessary, it is helpful to also define a polygonal location for the different reservoirs to be considered for storage. It is not necessary because the DSS by default looks for the cheapest reservoir in the immediate vicinity. However, specifying a region for reservoirs frees up computational power and time in actual practice by optimizing for reservoirs within the given region only.

Source Characteristics: This input for sources within the location specified above is itself a function of all the parameters identified for CO_2 sources in the third chapter. Recalling that they include volume, quality, pressure, type of plant, retrofit parameters amongst others, the output for source characteristics includes:

- Cost of capture on a per unit weight/volume of CO_2 basis
- Volume/scale of CO_2 emitted from the source
- Quality of CO_2 emitted

Reservoir Characteristics: Similar to the sources, reservoir characteristics within the specified location form an input to the DSS and are a function of the parameters identified for reservoirs in the fourth chapter. These parameters include depth, thickness, capacity, injectivity, pressure and containment parameters. All these parameters combine to generate outputs that form the input to the DSS and are:

- Cost of storage on a per unit weight/volume of CO_2 basis
- Capacity of reservoir to store CO_2
- Containment aspects

Transportation Inputs: Within the specified location, pipeline transportation of CO_2 depends on the different parameters identified in the fifth chapter and includes throughput, length, quality, terrain, pressure, political and regulatory consideration amongst others. These parameters combine to produce outputs which form the inputs to the DSS and are:

- Costs of pipeline transportation of CO_2 between any two 'cells' within the specified location
- Capacity of a pipeline with a specified cost
- The route that the pipeline takes

6.2.2: Constraints

Constraints imposed on a model are necessary for two reasons:

- To avoid abnormal behavior of the model
- To define the level of analysis (this is described in section 6.2.4: on outputs)

To obtain a meaningful output from the DSS evaluating sequestration options, the four major constraints that need to be imposed on the model include:

- Minimize cost of sequestration within the defined system boundaries – this is extremely important since the system boundaries define the level of analysis and output. For example, if transportation is considered alone, the output may be very different for a single source-reservoir matching than if the entire lifecycle cost is considered
- Capacity of reservoirs should match or exceed the volume of CO_2 emitted from a source over a given period of time
- Permitting and regulatory issues – these constraints will be imposed on both reservoir siting and pipeline routing

- Level of risk – this is related to the containment aspects of a reservoir. Depending upon the maximum level of risk acceptable, the model will select reservoirs with an equal or lower level of risk than the maximum acceptable risk.

6.2.3: Internal Calculations

After receiving the inputs and the constraints as discussed above, the model uses the given information to generate outputs through a series of internal calculations. The logical progression of calculations includes:

- Read source characteristics within given location
- Read system boundaries to decide level of analysis
- Read reservoir characteristics within given location
- Identify proximate reservoirs with matching capacities
- Read transportation inputs within given location
- Identify least-cost path from source to reservoir
- Depending on level of analysis required, produce output matching one or more sources to one or more reservoirs

6.2.4: Outputs

The final outputs from the model include:

- A matched reservoir for every source identified within the specified location
- Total cost of sequestration per unit weight/volume of CO_2 which integrates
    - Capture costs
    - Transportation costs
    - Storage costs

Based on the level of analysis specified, there are three different kinds of outputs that are generated from the model:

Level 0: This is basically a one-to-one matching process where a source is individually matched to a cheapest reservoir minimizing only the cost of transportation for that source without any consideration for possible synergies to be gained from multiple sources feeding to a common reservoir.

Level 1: This is the next level of many-to-one matching where several sources are matched to one large reservoir. This has the potential of reducing the cost of transportation by benefiting from common pipelines in an optimized network situation.

Level 2: This is the true overall system optimization where transportation, storage costs and capacities are all considered for multiple sources and reservoirs within the specified location producing the lowest total cost of sequestration.

6.2.5: Model Overview

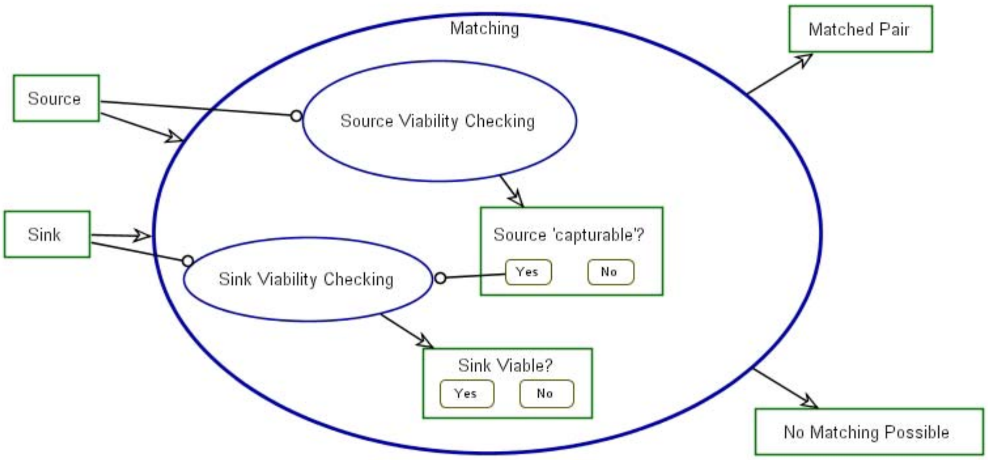

Figure 17: Model overview of the DSS

An overview of the model built using OPCAT is presented in Figure 17. One of the unique features of OPM is the formal graphical representation of the model and an equivalent natural language description that is generated automatically when creating the graphical model.

Matching consumes Source and Sink .
Matching yields Matched Pair and No Matching Possible.
Matching zooms into Source Viability Checking and Sink Viability Checking, as well as Sink Viable? and Source 'capturable'?.
    Sink Viable? can be Yes or No .
    Source 'capturable'? can be Yes or No .
    Source Viability Checking requires Source.
    Source Viability Checking yields Source 'capturable'?.
    Sink Viability Checking requires Sink and Yes Source 'capturable'?.
    Sink Viability Checking yields Sink Viable?.

Figure 18: Natural language description of Figure 17

The natural language description of the DSS Figure 17 is illustrated in Figure 18.

6.3: Case Study

As has been discussed throughout this thesis, pockets of information exist about the different aspects of geologic sequestration. As such, identifying any one location with complete information on all sources and possible reservoirs within the region and accompanying information on transportation parameters was not possible. Hence, a location was chosen as a possible 'best alternative' given available information on all the different aspects of sequestration and assumptions were made as required to fill in the voids. It is worthwhile to stress that this investigation is but a first effort at integrating various research efforts in the field of geologic carbon sequestration and as such an included case study is mostly illustrative of the capabilities of the DSS given adequate information.

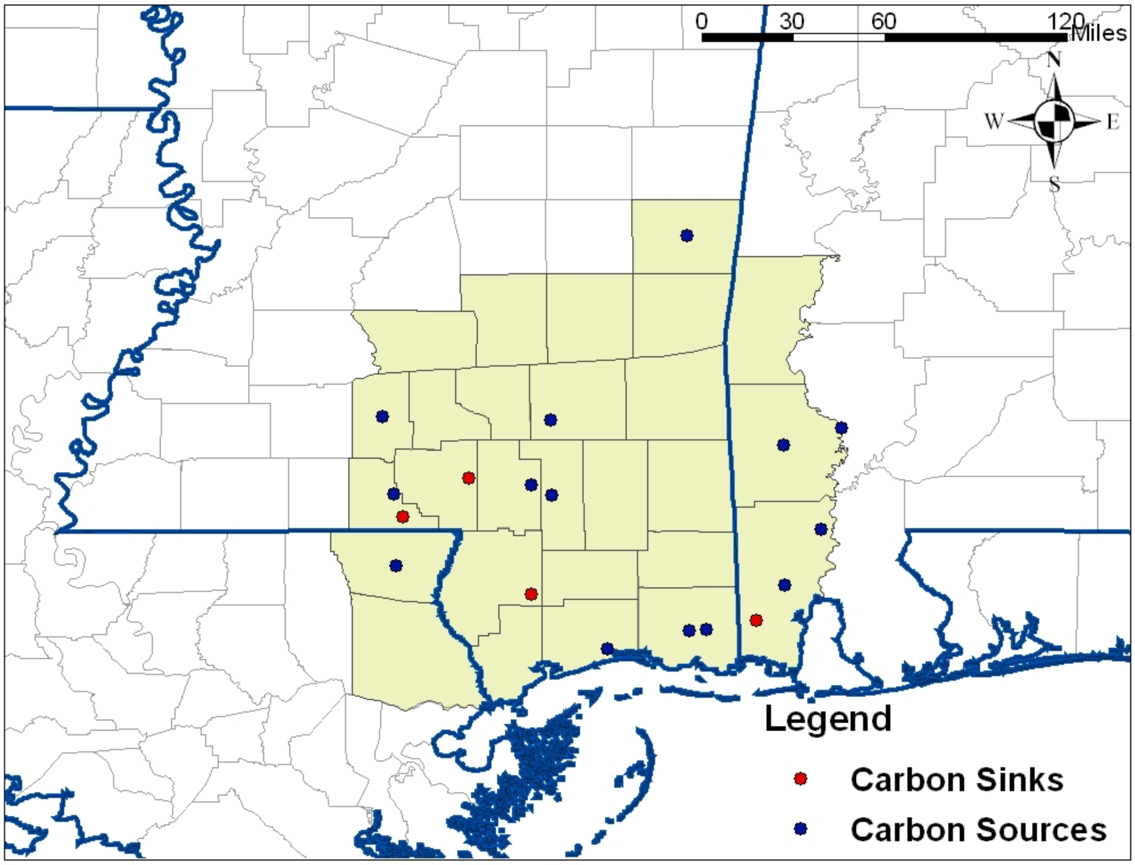

Figure 19: Region selected for case study.

6.3.1: Case Description and Methodology

As mentioned above, a region located mostly in the state of Mississippi and covering parts of Alabama and Louisiana in the US was chosen as a 'best alternative' with reasonable information on sources, reservoirs and transportation parameters to conduct a meaningful analysis. An illustration of the region is shown in Figure 19 with the selected counties shaded in yellow. Sources included both power plants and industrial processes. Two types of reservoirs were considered: depleted gas reservoirs and a deep saline formation. There was sufficient diversity in the topography to create different scenarios for transportation given different required levels of analysis. A more detailed description of the sources and reservoirs chosen along with details about other key parameters is available in Table 6.

Table 6: Case study data on sources, reservoirs and other parameters

SOURCE DATA

SOURCE	NAME	ANNUAL CO_2 EMISSIONS (tonnes)
1	Alabama Electric Coop Inc	4,028,993
2	Alabama Power Co	313,566
3	Alabama Power Co	12,435,918
4	Exxon Mobil	396,059
5	Mississippi Power Co	7,071,914
6	Mississippi Power Co	432,012
7	Mississippi Power Co	5,850,686
8	Mississippi Power Co	161,602
9	South Mississippi El Pwr Assn	477,000
10	Mississippi Power Co	113,909
11	South Mississippi El Pwr Assn	1,245,042
12	Gaylord Container Corp	5,065
13	Transcontinental Gas Pipe Line	5,191
14	Georgia Pacific	10,973

RESERVOIR DATA

RESRVOIR	TYPE	LATITUDE	LONGITUDE	CAPACITY
A	Deep saline formation	-88.32	20.59	unlimited
B	Depleted gas reservoir	-89.39	30.70	27,085,485
C	Depleted gas reservoir	-89.69	31.25	13,042,904
D	Depleted gas reservoir	-90.00	31.07	29,309,897

OTHER PARAMETERS/ASSUMPTIONS

1. Cost for crossing a cell with resolution of 30m X 30m is "1"
2. The average construction cost is $250,000 per mile for 8" pipelines
3. Based on (2), the average construction cost per cell (30m) is $4,600,
4. It is roughly estimated that the base case cost is $2,000 per cell
5. O&M cost is $3,100/km, independent of pipeline diameter
6. Compression cost are not included
7. IGCC power plant CO_2 transportation cost is less than $1 per tonne per 100km

Since this investigation was primarily a demonstration effort, assumptions for default values of certain parameters were used where information was scarce or not available. These assumptions were based on data in peer reviewed journals for similar cases and advice of industry experts.

Some of the factors that were not considered for the model included:

- Regulatory, social and political factors – these factors are difficult to quantify and represent in a spatial format
- ROW issues - while these were not considered for this study, they have been targeted for inclusion in future work on the GIS at MIT.

6.3.2: Results

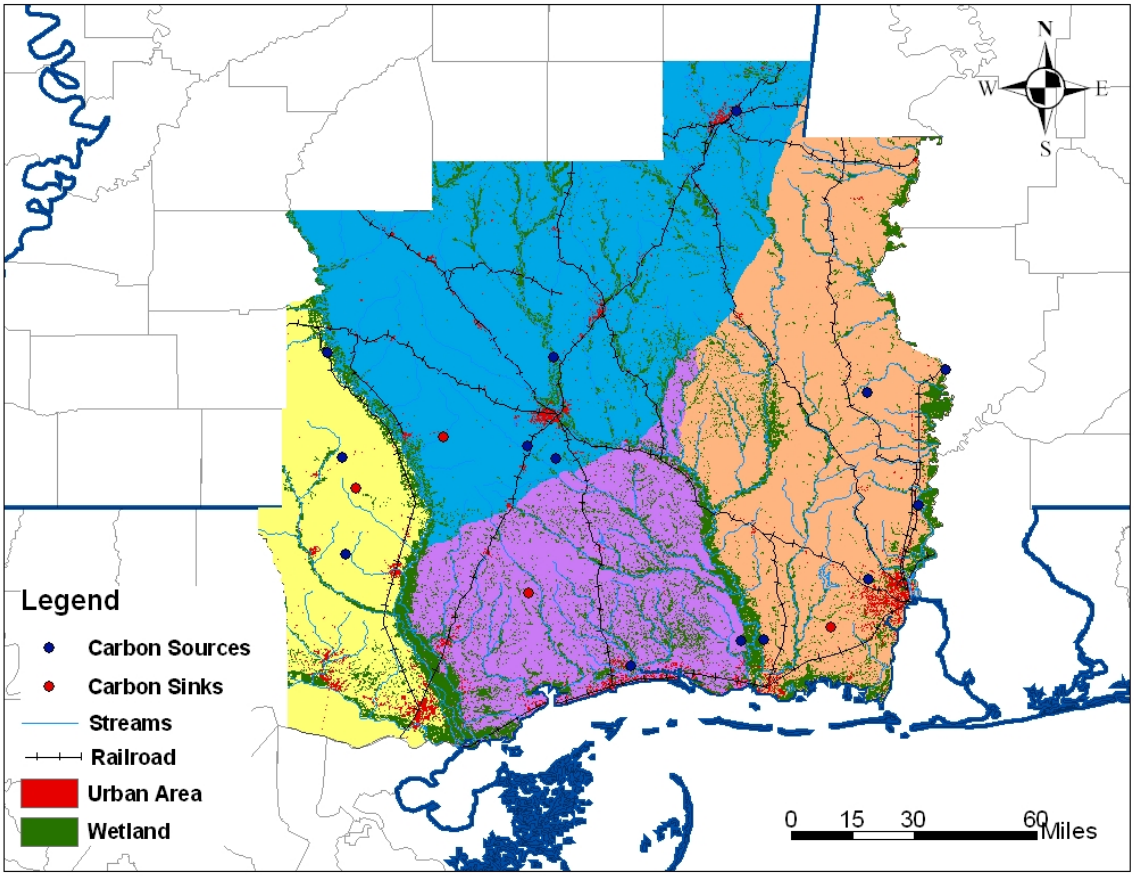

Figure 20: Level 0 analysis based on transportation cost alone on a one-to-one basis

As discussed earlier, there are different levels of analysis that can be conducted using the DSS. Figure 20 illustrates a Level 0 analysis where a source-reservoir matching is conducted on a one-to-one basis minimizing the transportation cost alone. The reservoirs are represented by alphabets and sources are represented by numbers. As can be seen in the figure, within each colored zone, there is only one reservoir and any source within the zone incurs the minimum transportation cost if matched with the reservoir within the zone. The boundaries of any given region largely coincide with natural boundaries such as wetlands. A detailed explanation of the costing methodology within the GIS is described in Section 4.2.1: of the chapter on CO_2 transportation.

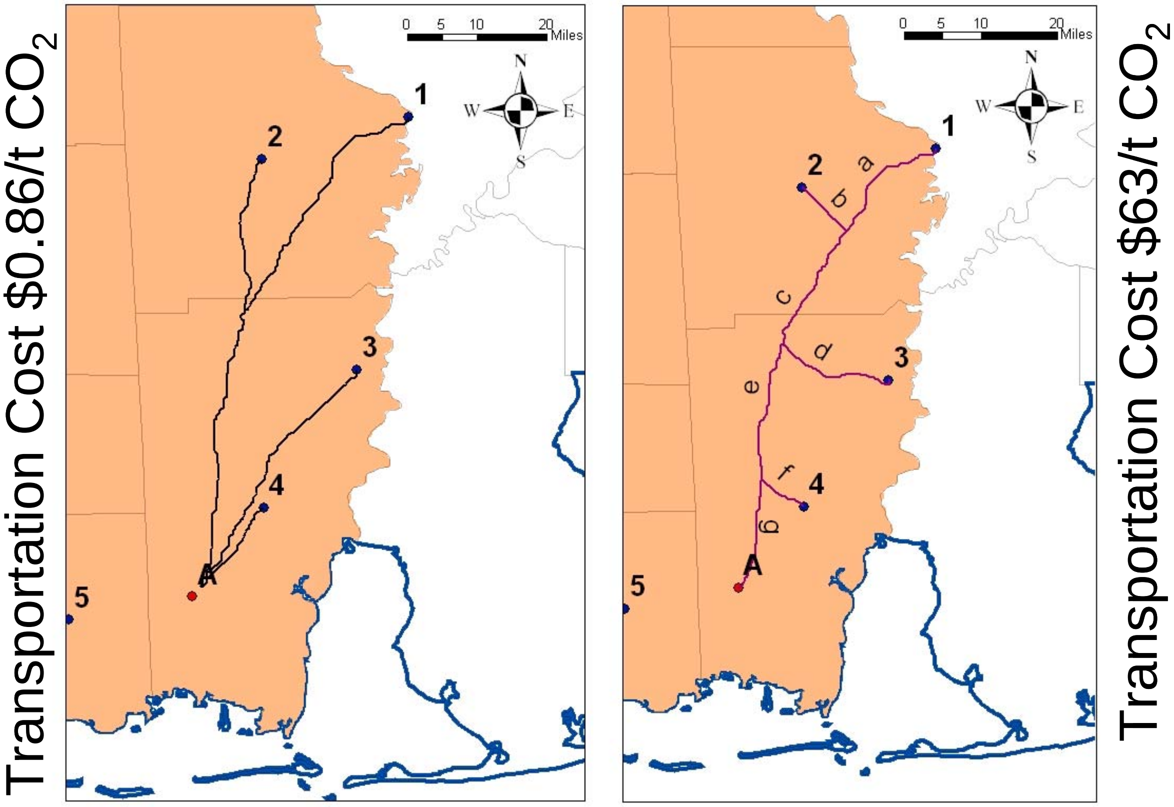

Figure 21: Level 1 analysis based on pipeline sharing and a transportation network

A Level 1 analysis is illustrated in Figure 21 where the cost of transportation is driven down from \$ 0.86/t of CO_2 to \$ 0.63/t of CO_2 transported. This is achieved by using a main transportation pipeline trunk from source 1 to reservoir A and having all the other sources within the region feeding into the main trunk pipeline. The optimization is done based on transportation cost alone by minimizing the total length of pipelines in the system without considering the capacities of the main trunk pipeline and the reservoirs.

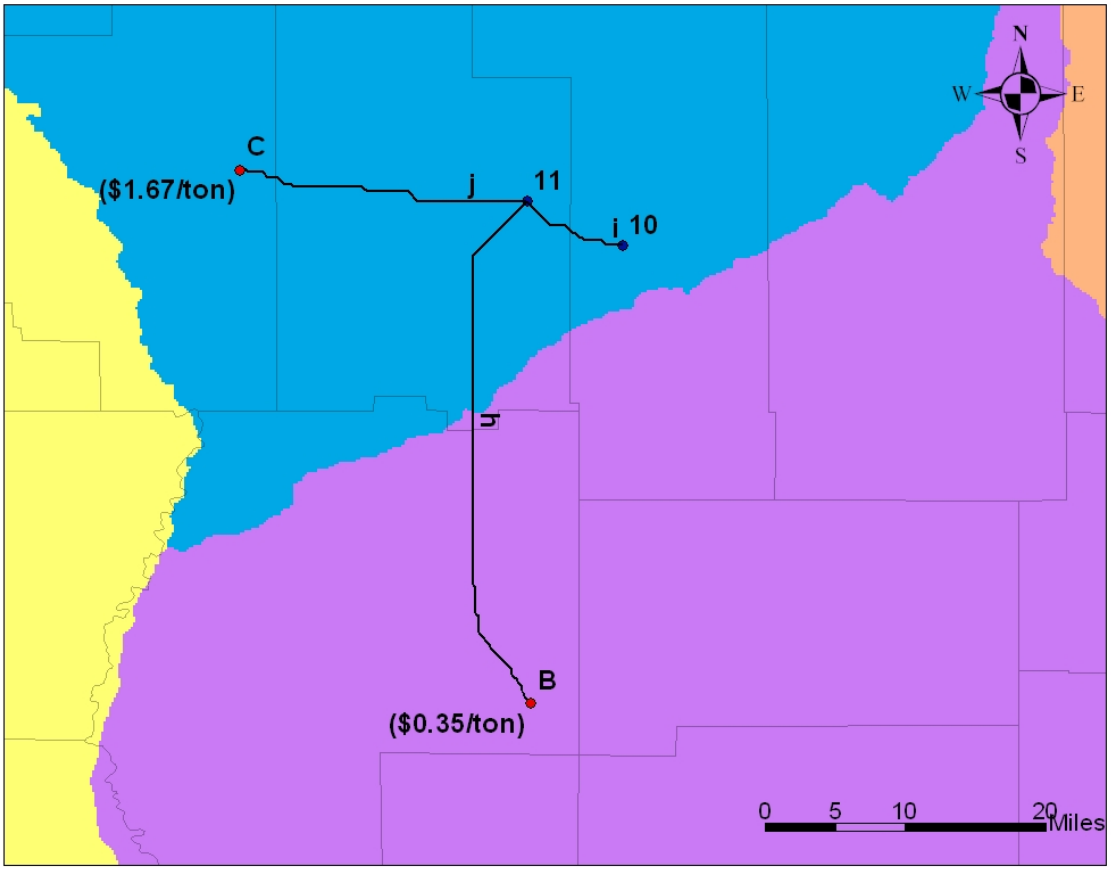

Figure 22: Level 2 analysis optimizing both transportation and storage cost

Figure 22 illustrates a very simple Level 2 optimization where both the transportation and storage costs are taken into account. Considering transportation cost alone, sources 10 and 11 find reservoir C as the cheapest option but if the cost of storage is included in the calculation, reservoir B emerges as the new least total system cost option.

<u>6.4: Conclusion</u>

As a first effort, the results of the systems analysis were promising and laid the framework for future efforts. As mentioned earlier, any parameter that was not considered in this round of analysis but which could be deemed in the future to influence the cost of sequestration can be added as a cost layer to the analysis. This renders the architecture of the system modular and flexible. As with parameters, the framework for constraints is also modular in nature and allows for the inclusion of further constraints as and when deemed necessary. Thus, as has been discussed in the system evolution section and subsequently illustrated in the case study, different levels of analysis with meaningful outputs can be conducted given adequate information. This system-level analysis also identifies deficiencies in current data hindering conducting such an analysis. Thus, as a first effort, the DSS has illustrated that the GIS is a very promising tool to conduct systems analyses for carbon capture and storage opportunities. Nevertheless, there exists significant opportunity to develop on this with more complete information.

Currently, given all the factors that are considered for the analysis, the system can calculate CO_2 transportation and storage costs with high reliability. Estimates of costs for capture are less precise and depend upon the assumptions made for the values of the different parameters determining the cost of CO_2 capture. The DSS can thus calculate the individual costs of CO_2 capture, transportation and storage and the system cost of sequestration. As the efforts at information collection progress and are incorporated into the GIS, the outputs of the system will become more reliable. These efforts at data collection and cataloging are being spearheaded by federally and state funded entities such as the MIDCARB which has since segued into NATCARB to signify its change in focus from the mid-continental US to a more nationally oriented one. Regional partnerships such as the SERCSP and the WCRCSP have also been contributing to these efforts.

7: CONCLUSIONS AND RECOMMENDATIONS

7.1: Conclusions

As a first effort at systems analysis to obtain a view of the bigger picture, the results look promising. The accomplishments of this investigation can be listed as:

1. Developed a systems framework for analyzing carbon sequestration options. This helps in evaluating different options with one common indicator of lifecycle cost.
2. Implemented tools in the GIS to conduct the analysis.
3. Identified important interactions between different stages of the sequestration process such as the matching of sources and reservoirs based on both transportation and storage costs.
4. The systems analysis also identifies areas that warrant further research such as storage in unmineable coal seams due to the niche opportunities that they offer.

The wide ranges in cost estimates for capture indicate the lack of data to calculate accurately the possible cost of sequestration. The biggest advantage of a systems analysis is the lifecycle cost of sequestration as an output. This enables the comparison of different sequestration options on a common scale. Finally, the GIS is a promising tool for analyzing CCS opportunities but is only as good as the underlying data driving the analysis.

7.2: Recommendations for Future Work

Recommendations at the end of this investigation include:

- More aggressive efforts at data collection and chronicling need to be undertaken
- Detailed algorithms for evaluation & optimization need to be developed
- Incorporate non-technical factors such as political sensitivity, social acceptability into the analysis

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