Report Title: "*U.S. China Carbon Capture and Storage Development Project at West Virginia University*"

Final Technical Report

Reporting/Project Period: March 1 2012 – December 31, 2013

Principal Author, Project Director & Principal Investigator: Jerald J. Fletcher

Report Issue Date: March 31, 2014

DOE Award Number: DE-FE0008344

West Virginia University Research Corporation

886 Chestnut Ridge Road, PO Box 6845, Morgantown WV, 26505

DUNS: 191510239

Project Director & Principal Investigator: Jerald J. Fletcher

Phone: 304-293-5499

Fax: 304-293-3752

Email: JJFletcher@mail.wvu.edu

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Abstract

The original overall objective of this activity was to undertake resource evaluation and planning for CCS projects and to describe and quantify the geologic, environmental, and economic challenges to successful development of large-scale CCS in China's coal sector.

Several project execution barriers were encountered in the course of this project, most notably a project stop/delay due to funds availability/costing restrictions from the US State Department to the US Department of Energy at the end of CY2012, which halted project execution from January 2, 2013 to April 1, 2013. At the resolution of this project delay, it was communicated to the project team that the overall project period would also be reduced, from a completion date of February 28, 2014 to December 31, 2013. The net impact of all these changes was a reduction in the project period from 24 months (3/1/2012-2/28/2014) to 22 months (3/1/2012-12/31/2013), with a 3 month stop from 1/1/2013-3/31/2013. The project team endeavored to overcome these project time impacts, focusing heavily on technoeconomic modeling that would be deliverable under Task 3 (Ordos Basin Feasibility Study), and choosing to abandon the full investigation into the Demonstration Site (Task 4) due to the reduced project time.

The ultimate focus of this project changed to work with the Chinese on a carbon atlas/geologic characterization, and on mechanisms for CO2 storage options from high-quality streams within China.

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Project Performance

This report summarizes the activities of Cooperative Agreement DE-FE0008344 (U.S China Carbon Capture and Storage Development Project) with the West Virginia University Research Corporation (WVURC) during the project period.

The project is composed of a project management task, and three research tasks:

Task 1—Project Management and Planning
Task 2— US-China Communication and Collaboration on CCS Technologies
Task 3— Ordos Basin Feasibility Study
Task 4— Demonstration Site

This report outlines the approach taken, including specific actions by subtask. While task 4 is still listed for completeness, minimal work was undertaken on this task in the overall project period, due to time limitations. The majority of effort was focused on the US-China Collaboration and Ordos Basin Feasibility Tasks.

Task 1 – Project Management and Planning

Subtask 1.1. – Project Management Plan

Approach

This task will document the overall approach to the management of the project. This document will include a summary of Risk as developed from Subtask 1.2, a Milestone Log, the funding and cost profile, and the Project timeline. The deliverable under this task is a PMP Draft delivered within 60 days of project award.

Results and Discussion

Project schedule reductions of approximately 5 months restricted some of the proposed work. These restrictions were communicated with DOE, and project management plans were updated throughout the project.

Subtask 1.2. – Risk Management Plan

Approach

This task will document the significant technical, resource, and management issues that could impact project success. This document will contain a risk register that will document the risk item, the consequence, and the strategies to mitigate the risk. The initial risk register will be reflected in the PMP. The deliverable under this task is an initial risk register included in the PMP. The RMP will be prepared within 60 days of project award.

Results and Discussion

Project schedule reductions of approximately 5 months restricted some of the proposed work. These restrictions were communicated with DOE, and project management plans were updated throughout the project.

Technical risks associated with data availability were experienced throughout the project, and the team worked to mitigate these impacts on the economics and CO2 network studies. Data acquisition from China continues to be a challenge for international collaborative work, as some data is seen as protected within China, and in some cases data that may highlight other issues (air quality, water quality, technical difficulties) is simply not provided. The WVU team will continue to develop and foster relationships with Chinese research teams to facilitate stronger research in the future.

Task 2 – US-China Communication and Collaboration on CCS Technologies

Subtask 2.1. – Construct Data Repository

Approach

A repository for surface and subsurface data required to evaluate the CO_2 storage resource in the Ordos Basin and to evaluate local sites for potential demonstration of geologic storage will be constructed in cooperation with Shenhua, SIEG and other industrial partners and Chinese academic collaborators.

Results and Discussion

The project team worked with Chinese academic and industrial partners to develop data sharing mechanisms and a data repository for geologic information.

While work with the Chinese universities was very positive, information and data availability through the Shenhua group was problematic, and activities in this portion of the basin did not receive Chinese government approval of the next phase of work. For the universities, successful work was performed with Professor Xiaochun Li (CAS-IRSM, Wuhan) for the exchange of information pertinent for CCUS and the development of a draft geodatabase. Additionally, the team hosted Zhi Zhong, a graduate student from the Chinese University of Geosciences in Wuhan. Data was generated through public sources and integrated with previously acquired data from studies at WVU.

Subtask 2.2. – Project Meeting

Approach

Participate in project meeting including preparation of all documents and reports for discussion with the Chinese research teams before delivery to USDOE and NEA

Results and Discussion

The project team worked with Chinese academic and industrial partners to develop data sharing plans and possible collaborative work plans.

Team researchers met with Wang Xiangzeng of Shanxi Yanchang Petroleum Group on shale gas development in the southern Ordos basin and the use of CO2 for fracture stimulation and enhanced gas recovery, and also discussed ongoing EOR projects. Undertook detailed discussions on CO2 emission sources in the Ordos and Qinshui basins and utilization of CO2 for fracture stimulation and EOR with Prof. Li Xiaochun and associates from the Chinese Academy of Sciences - Wuhan.

Met with members of Shaanxi Yanchang Petroleum Group including Dr. Xiangzeng Wang to discuss CO2-EOR in Ordos basin and compare with operations in US. Also arranged trip to shale gas rig site and made presentations on shale gas.

Task 3 – Ordos Basin Feasibility Study

Subtask 3.1. – Acquire Information

Approach

Develop information sets of selected geologic storage targets, including oil and gas fields, saline aquifers and deep unminable coal beds.

Results and Discussion

Dr. Tim Carr met with Professor Li Xiaochun and colleagues at the Institute of Rock and SoilMechanics (IRSM) of the Chinese Academy of Sciences (CAS), and Professor Yao Guangqing and colleagues at the China University of Geosciences in Wuhan. Discussion centered on methods to evaluate resources for shale gas and carbon capture, utilization and storage. Similar discussions were undertaken with Professor Huang Zhanbin’s group at the School of Chemical and Environmental Engineering of the China University of Mining and Technology in Beijing. Arrangements were made for Dr. Tao Zhu to come to WVU for a one year post-doctoral visit focused on greenhouse gas emissions from unconventional resource extraction.

Subtask 3.2. – Evaluation of selected oil fields for potential value-added CCS.

Approach

Geologic and engineering teams will expand and refine base studies for selected fields that can be used as analogs.

Results and Discussion

The primary focus under this task was the support of two PhD students (Liaosha Song and Zhi Zhong) working on CCUS in China and the USA. As part of a PhD dissertation Zhi Zhong moved forward loading data into the fluid flow simulator from CMG that will be used to develop a full-field CO2-EOR simulation of the Stringtown Field, West Virginia. The field is very similar to upper Paleozoic oil fields in the Ordos basin, China and will be compared to these fields using information from Yanchang Petroleum. Both the Appalachian and Ordos basins are dominated by tight fluvial sandstone reservoirs that are at relatively shallow depths and near the critical depths for super-critical storage of CO2. Primary investigation will be relative to how efficiently CO2 can be injected in these fields, and whether it is possible to recover sufficient hydrocarbons to at least partially offset operating costs and store significant volumes of CO2.

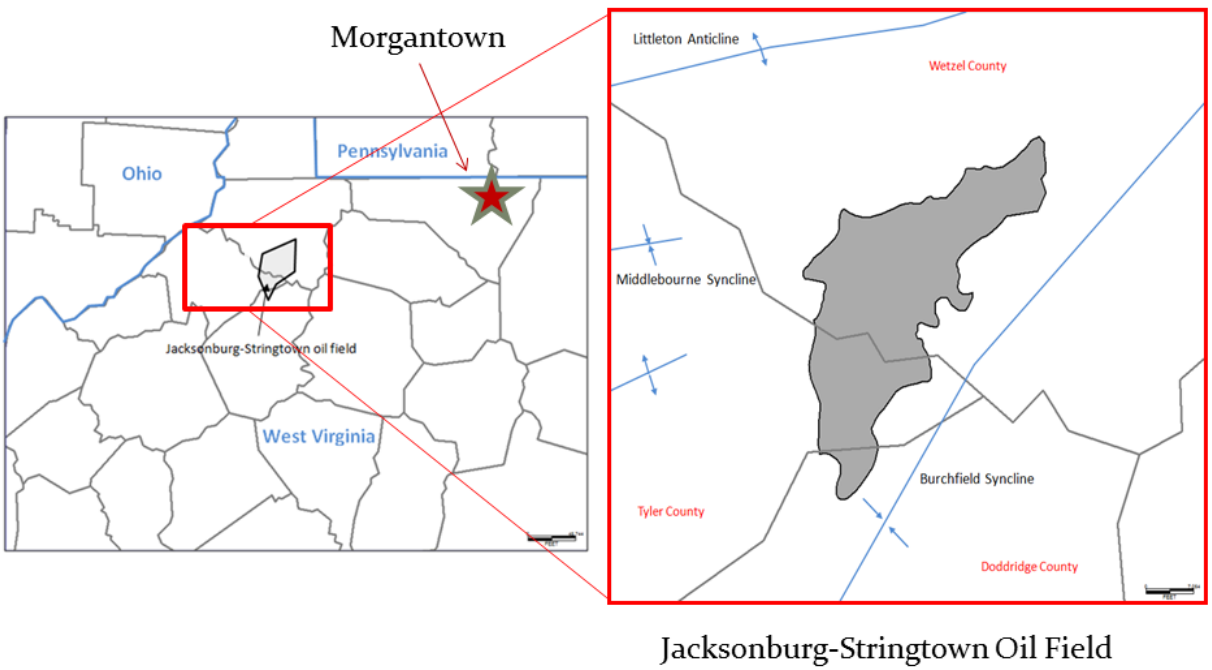

Figure 3.2.1 Location of Jacksonburg-Stringtown Oil Field

Liaosha Song is starting a project looking at shale gas in the US and China and the potential for the use of CO2 in fracture stimulation. This would replace water and relieve the stress on water supplies in such areas as the Ordos and south Texas (i.e., Eagle Ford). This study has obvious implications for CO2 storage and decreased CO2 emissions with the substitution of gas for coal.

A Post Doc / Visiting Scholar, Dr. Tao Zhu from Chinese University of Mining and Technology performed work to document surface disturbance and emissions (air and water) of shale gas development. This would again have impact of development in China and on documenting the climate and environmental impact.

Additionally, the team presented at the International Pittsburgh Coal Conference (IPCC) in Beijing on technical issues of shale gas in the United States and compared it to developments in China.

Subtask 3.3. – Evaluate Major Saline Aquifers Geologic CO2 Storage Simulation

The Ordos Basin is the second largest basin in north-central China, with an area of $37X10^4 km^2$. The basin contains abundant oil, natural gas and coal resources (Figure 3.1). The abundant energy resources have contributed to the Ordos Basin becoming a significant site for energy-based industry, and the resulting large increase in CO_2 emissions. In 2008, the Shenhua Group initiated construction of the largest coal-to-liquid (CTL) project in world. Associated with operation of the CTL project CO_2 emissions are expected to reach approximately 3.67 million metric tons (Mt) per year. In order to address the CTL project emissions as a contribution to mitigating greenhouse gases, Shenhua plans to capture and store inject CO2 into geological formations (i.e., Carbon Capture and Storage – CCS). In order to support the Shenhua CCS project, WVU undertook simulation studies.

Using previous data gathered from public sources six preferred reservoir-cap rock combinations selected as initial target formations for CO_2 injection into saline formations (Figure 3.2, 3.3). Numerical simulations of different injection scenarios were generated to get detailed information on the sequestration capacity, stable injection time, CO_2 plume distribution and reservoir pressure distribution at different time steps for each formation. Through comparing and analyzing different scenarios' simulation results, the objective is to provide more quantitative and visual estimates for feasibility evaluation and scenario optimization of the 0.1Mt/yr CO2 injection project. A Numerical Reservoir Simulator developed by Computer Modeling Group (CMG) was used to develop simulation models.

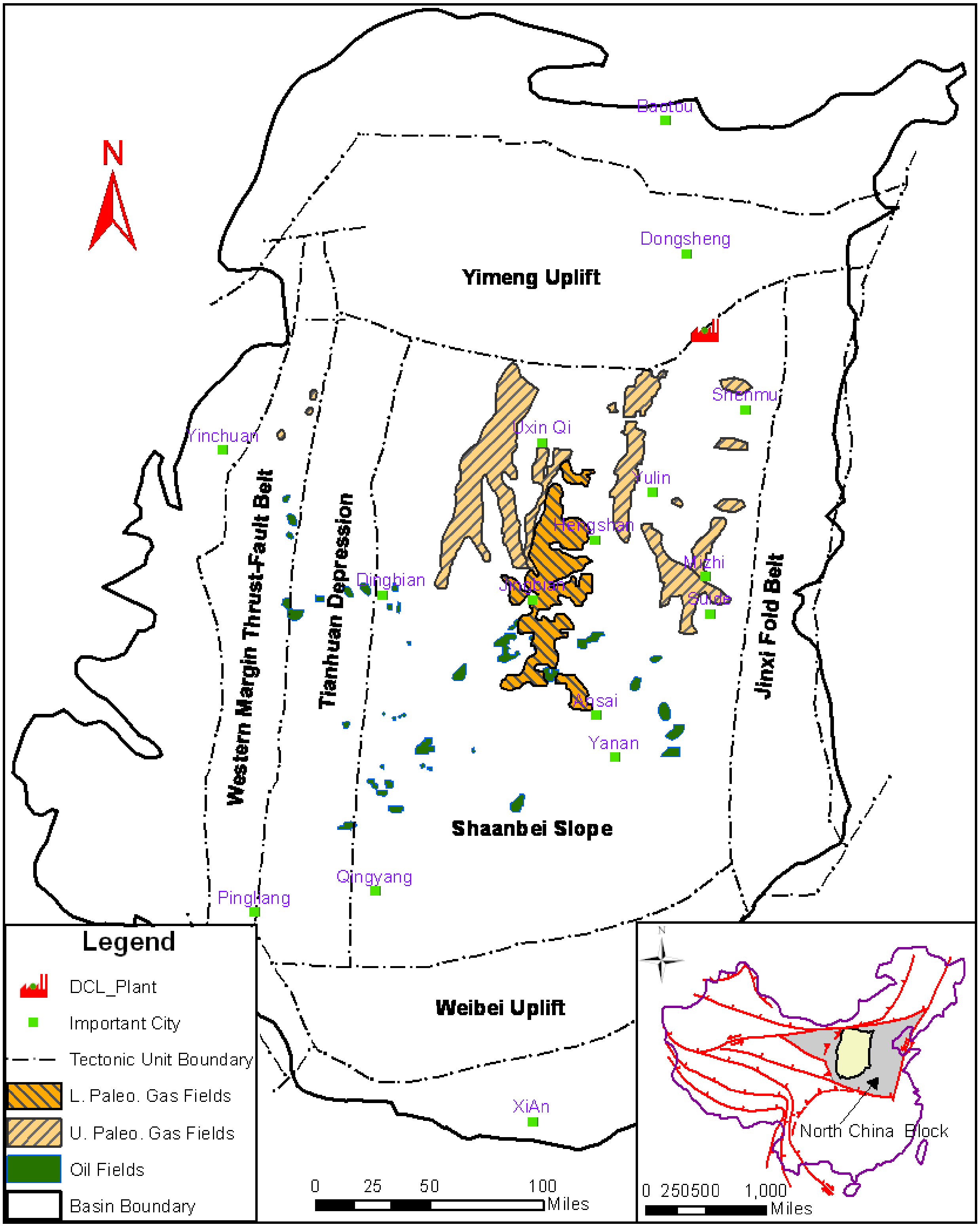

Figure 3.3.1. A map of the Ordos Basin showing the location of major tectonic units, oil and gas fields and the Shenhua CTL facility.

DATA ACQUISITION

Based on literature review and discussions among China University of Geoscience, Chinese Academy of Sciences Institute of Rock and Soil Mechanics, Shenhua and Perking University geologic parameters were generated for a regional study of the Ordos basin. A geologic model for the area surrounding the injection location was constructed at West Virginia University Department of Geology & Geography (Figure 3.2). The geomodel at the injection location was used for the numerical simulation of different injection scenarios.

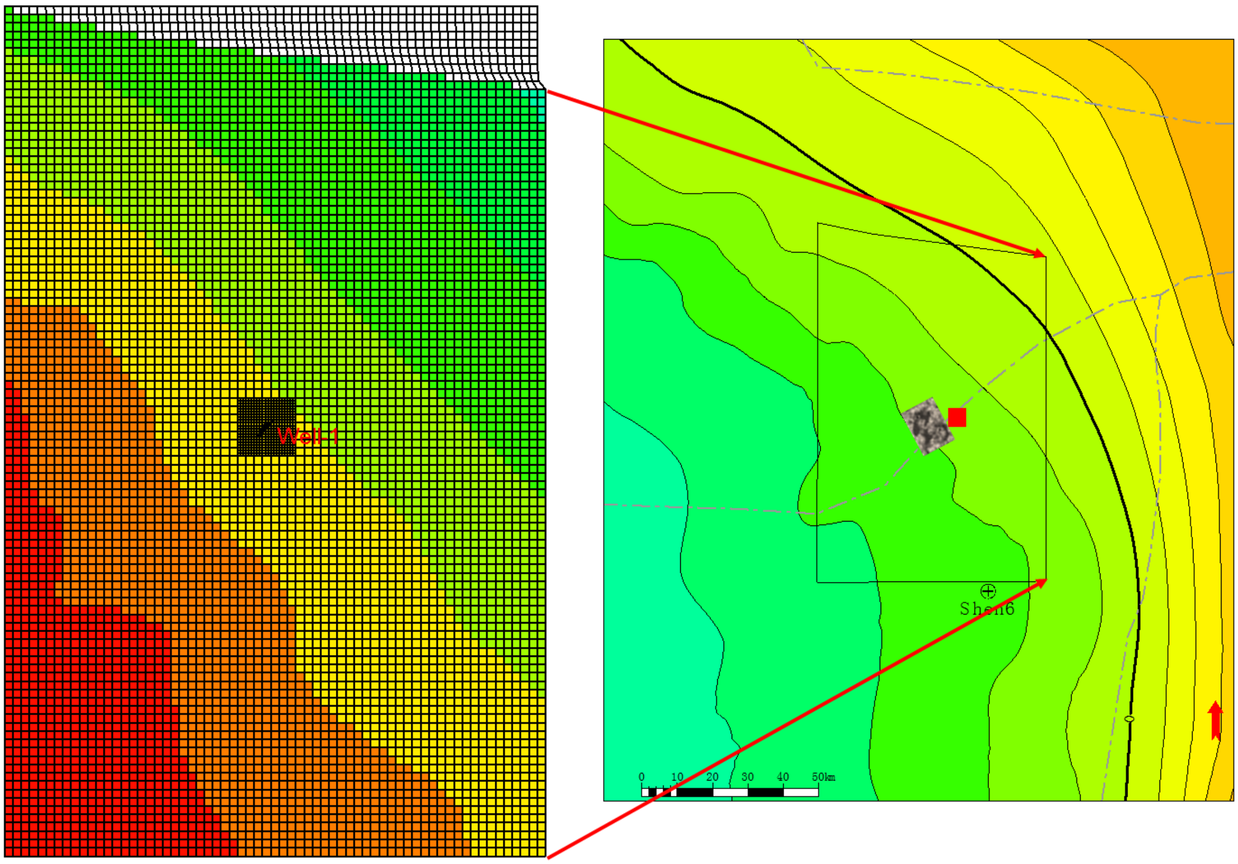

Figure 3.3.2. Reservoir model of the injection location in Ordos basin. Gridded reservoir data is at a finer and finer scale approaching the injection well.

Reservoir input properties

According to information provided such as porosity, permeability, effective thickness, injection pressure, numerical simulation several layers. The Shiqianfeng layer had the best results and simulations were undertaken under a number of scenarios. Information on the reservoir properties is shown (Tables 3.3.1-3.3.2).

No	Reservoir-Seal Assemblage	Top Depth	Reservoir thickness	Effective thickness	Porosity %	Permeability mD
1	Ermaying-Heshanggou Group	1160	70	50	5-8	0.15-0.4
2	Liujiagou Group	1375	15	14	4.5-7	0.1-0.3
3	Shiqianfeng Group	1570	70	65	6-8	0.2-0.5
4	Shangshihezi-Xiashihezi Group	1920	60	50	6-9	0.2-0.6
5	Shanxi, Taiyuan-Ma5	2190	20	10	2-3	0.3-0.5
6	Ma3-1 members	2580	50	10	2-3	<0.5

Table 3.3.1 Main reservoir properties of the six formations from Shenhua and other sources,

Wellhead injection temperature	20℃
Wellhead injection pressure	20 MPa
Well bottom injection pressure	30Mpa
Injectivity rate of single well per day	146391 m3/d
Effectiveness of well open	0.9452
Simulate period	20 years

Figure 3.3.2. Simulation inputs for Shiqianfeng layer from Shenhua and other sources.

Two equations were were used for calculation of reservoir pressure and temperature:

$$T(^\circ C) = 0.0319 \times d(m) + 10.5$$

$$P(Mpa) = -0.0092 \times h(m) + 11.028$$

STATIC RESERVOIR MODELING IN CMG

Four layers representing the Liujiagou, Shiqianfeng, Shihezi and Shanxi groups were used to generate a geomodel and then imported into the simulator CMG (Figures 3.5-3.6). Each grid is 300m*300m, and each refined grid adjacent to the wellbore is 100m*100m.

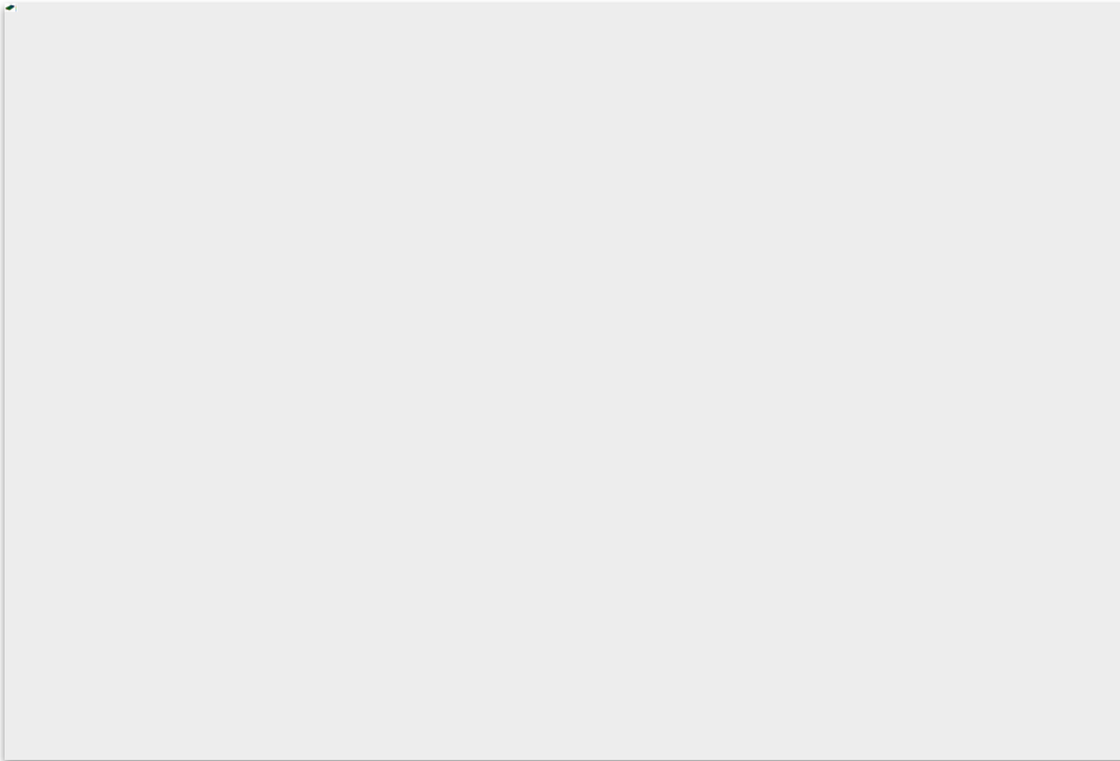

Figure 3.3.3. Top surface view of 3-D reservoir modeling around injection location

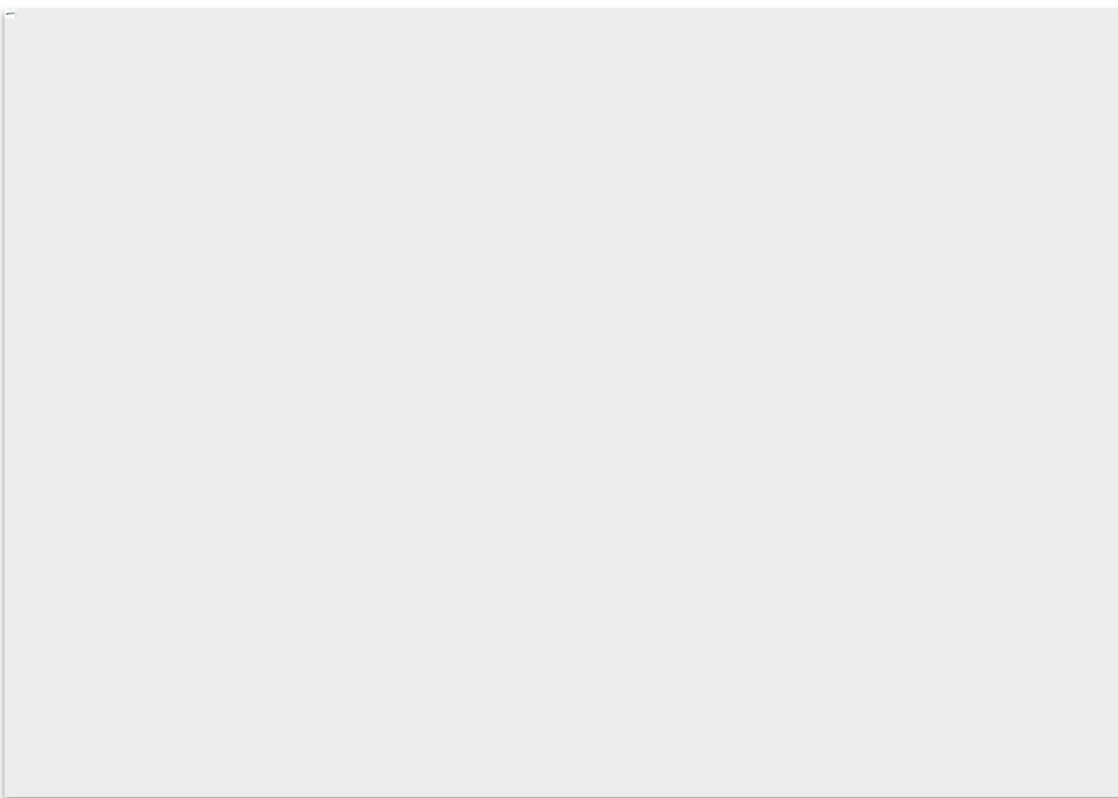

Figure 3.3.4. Lateral 3-D view of reservoir modeling around injection location

For the reservoir inputs:

a) Two property settings were used for simulation, one set is from the previous reports from Shenhua on May, 2010 (Table 3.3.1), the other set is the revised based on input from Shenhua and others (Figure 3.3.3)

	Permeability (md)	Porosity
Liujiagou group	0.097	0.047
shiqianfeng group	0.131	0.0549
shihezi group	0.148	0.0595
shanxi/taiyuan group	0.24	0.0469

Table 3.3.3 Revised reservoir properties for the four formations used in the simulation.

Since logging and seismic data were not available, all the layers are assumed to be homogenous which means that similar properties are distributed throughout the entire layer.

b) Considering the reservoir fracturing pressure and the injection amount, and using the pressure and temperature equations as references, the injection condition and constraints have been set as the follow (Figure 3.3.4):

Injection Temp	25℃
Maximum Injection Pressure	22.866 MPa
Injection Gas rate	125,698 m3/d
Well open time ratio	1
Simulation time	50years

Table 3.3.4. Reservoir simulation inputs and (0.1Mt/year=0.1*10^6*458.8m^3/365=125,698 m^3/day).

FLUID FLOW RESERVOIR SIMULATION

For simulation of injection of CO_2, three scenarios have been designed to approach the desired 0.1 Mt/yr injection amount:

a) Case1: One vertical well; without hydraulic fracturing

b) Case2: One vertical well; with hydraulic fracturing

c) Case3: One horizontal well; with hydraulic fracturing

Based on these three scenarios, the advantage of the hydraulic fracturing and horizontal well drilling in the proposed project are confirmed by the simulation results. Since information on geochemistry of the lithology and fluid contents of the target injection units are unavailable, we did not consider geochemical reactions during simulation scenarios. Geochemical reactions could be important. It is recommended that data on the matrix (i.e., rock) and formational fluids be acquired to address these questions. Simulation time was set for 50 years.

Results

Based on the available data for reservoir parameters (e.g., thickness, porosity and permeability), the conclusions for three different scenarios are:

Case1: Vertical well; no hydraulic fracturing

Shiqianfeng layer has the largest capacity for CO_2 sequestration and injection rate (Figure 3.3.5)

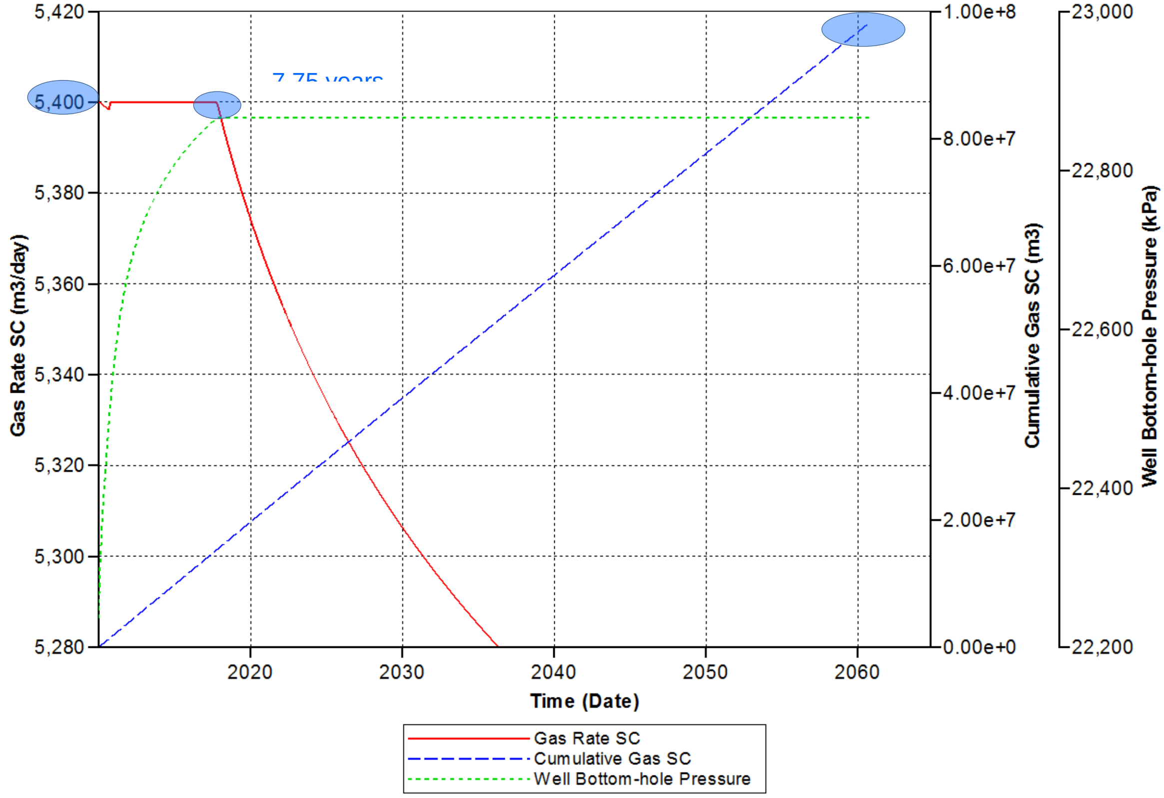

Figure 3.3.5, Results of simulation case 1 Shiqianfeng Group. **Shiqianfeng Group**

If the injection rate is 5,400m^3/day, the stable injection is maintained for 7.75 years and declines rapidly. Again this is a result of the model limits and the rapidly expanding extent of the pressure perturbation and increased CO_2 saturation reaching the no flow boundaries of the model (Figures 3.3.6, 3.3.7). The cumulative injection through 2060 is 1e8m^3, which an average of 4,360 tons/year. However, the average injection rate is severally affected by the model limitations. Well spacing under the revised property settings is beyond the extent of the static geomodel and would have to be very large to prevent operational interference.

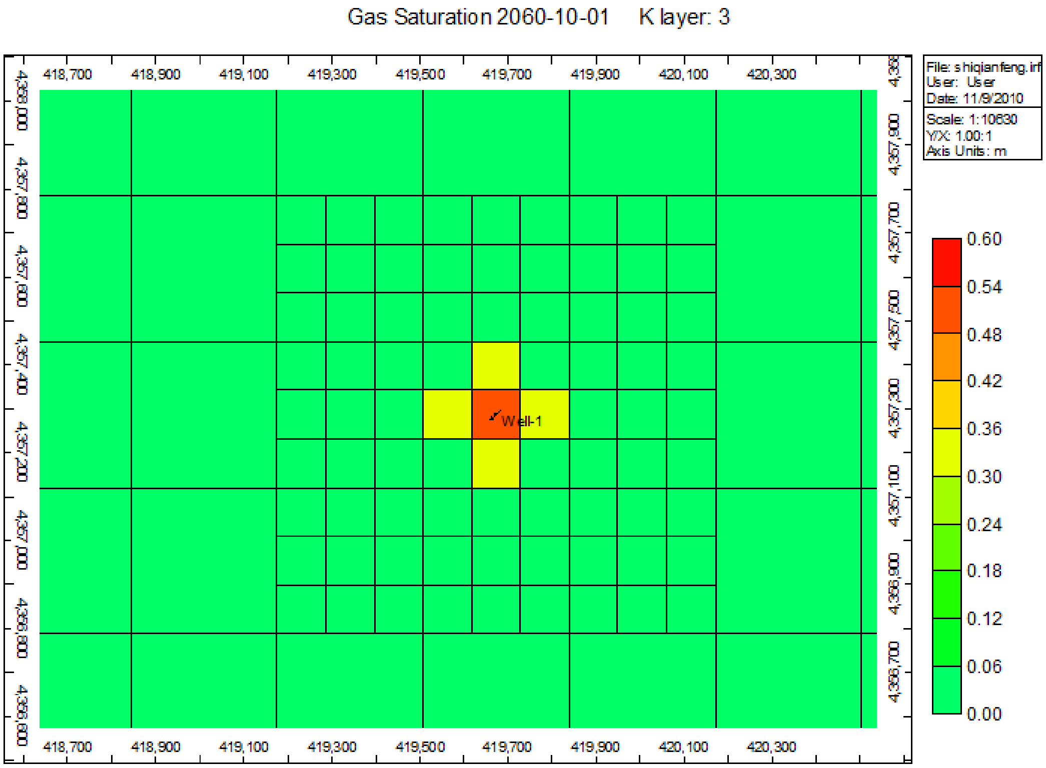

Figure 3.3.6. Distribution of CO_2 saturation in the Shiqianfeng Group using revised parameters after injection for 50 years.

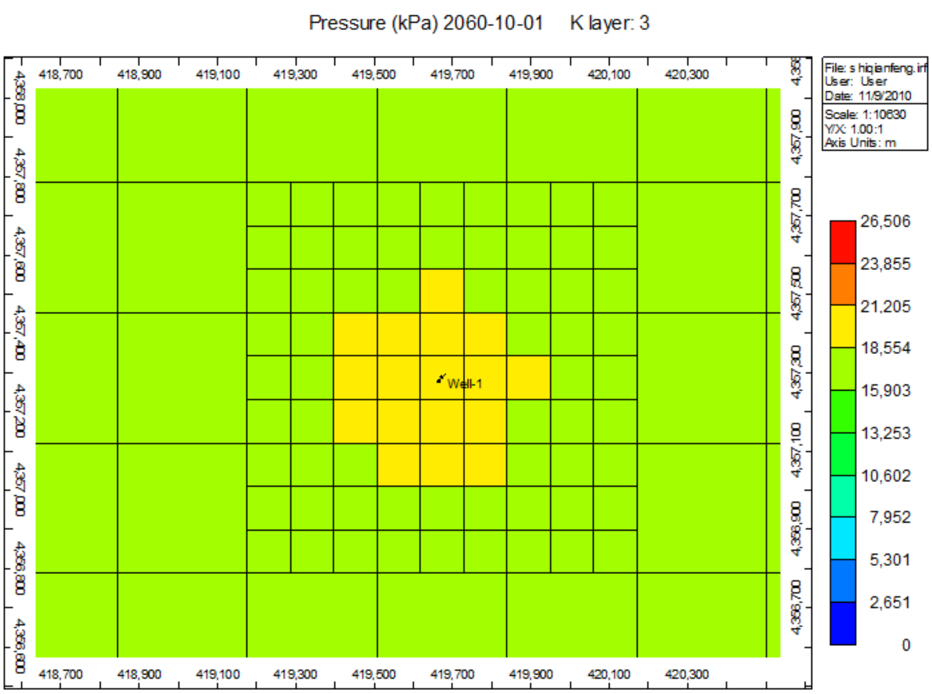

Figure 3.3.7. Distribution of the pressure perturbation in Shiqianfeng Group using revised parameters after injection for 50 years. Perturbation has reached the lateral limits of the model.

Case2: Vertical well; hydraulic fracturing

With hydraulic fracturing, CO_2 injection amount in the Shiqianfeng layer can increase by 20% (Figure 3.12). Given that the Shiqianfeng layer has the highest injection rate and greatest storage capacity of the four layers examined under the revised parameters, hydraulic fracturing of the Shiqianfeng layer was introduced into the simulation to determine the degree injection rate of CO_2 could be improved. The fracturing setting in CMG is as follows:

Fracture width=0.0025m

Half -length=100m

Fracture orientation=J

Permeability in fracture=410md

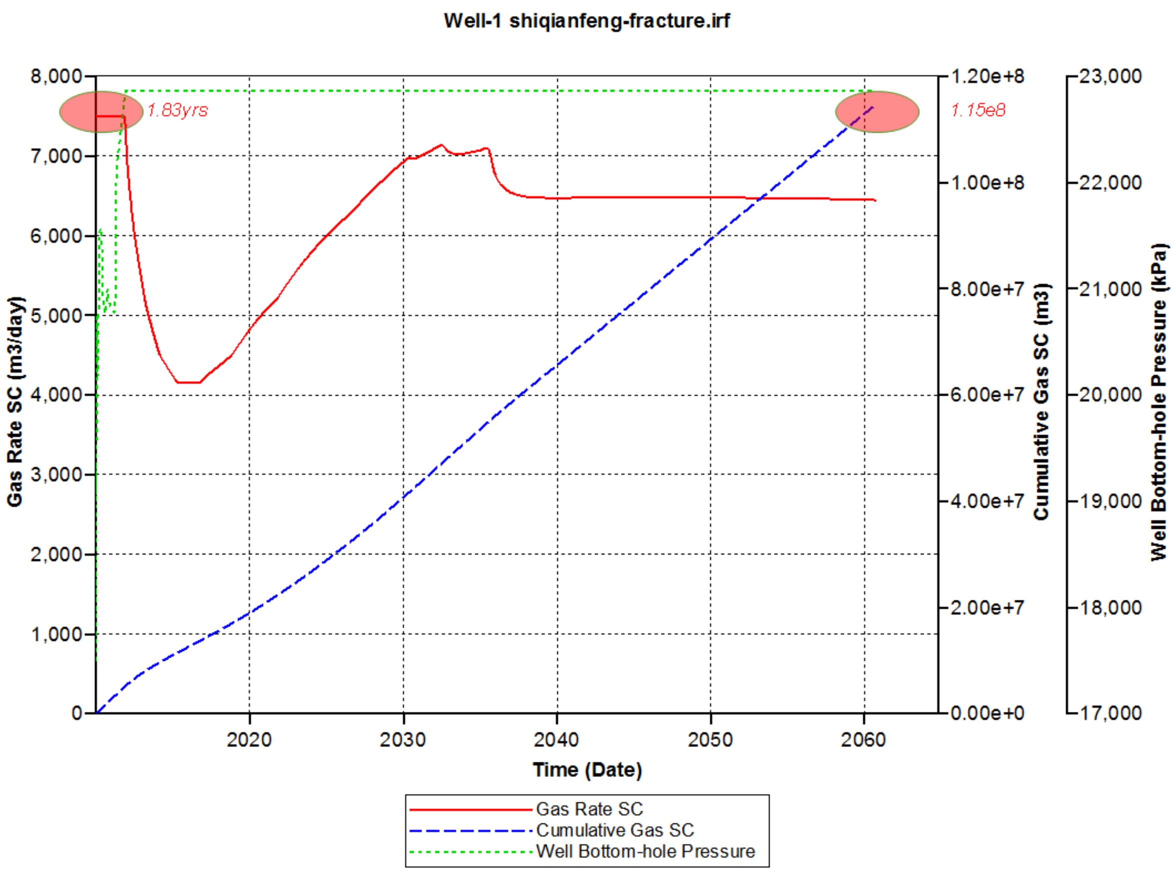

Figure 3.3.8, Results of simulation case 2 Shiqianfeng Group. **<u>Shiqianfeng Group</u>**

Again, the area affected by elevated CO_2 concentration and pressure perturbation reached the no flow boundaries of the model, which severally affects the results (Figures 3.3.9 and 3.3.10). If the injection rate is 7,500m^3/day, and the stable injection rate is maintained for only 1.83 yrs, the cumulative injection is 1.15e8m^3, which is 5,014 tons/year.

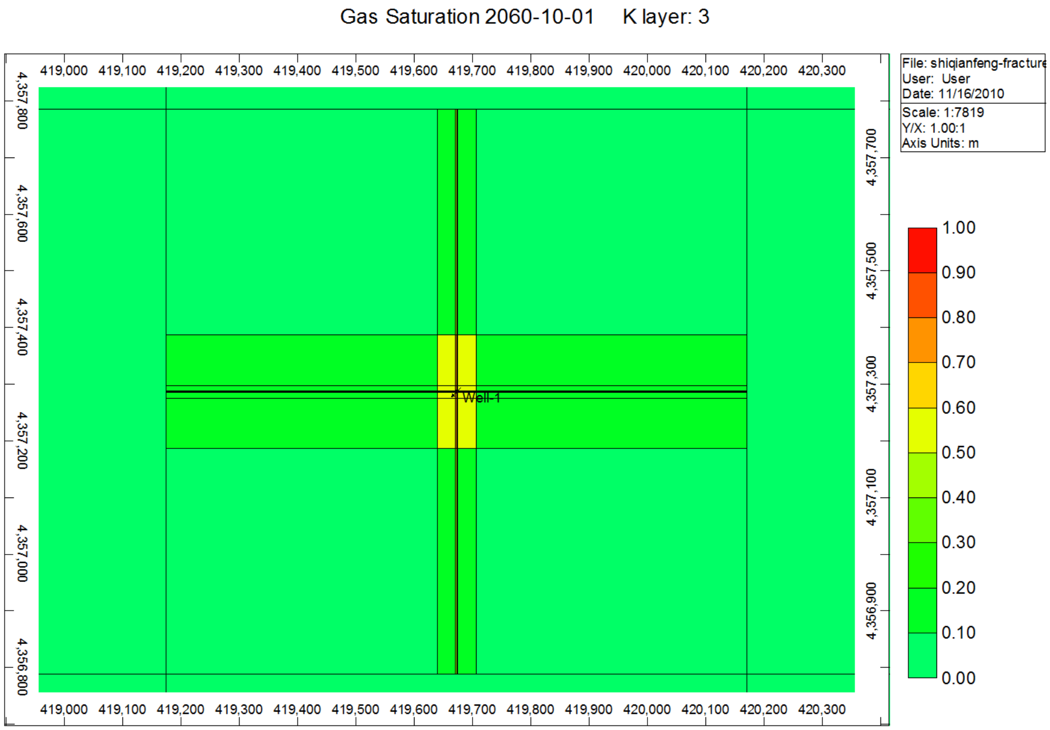

Figure 3.3.9. Distribution of CO_2 saturation in the Shiqianfeng Group using revised parameters and introducing hydraulic fracture stimulation after injection for 50 years.

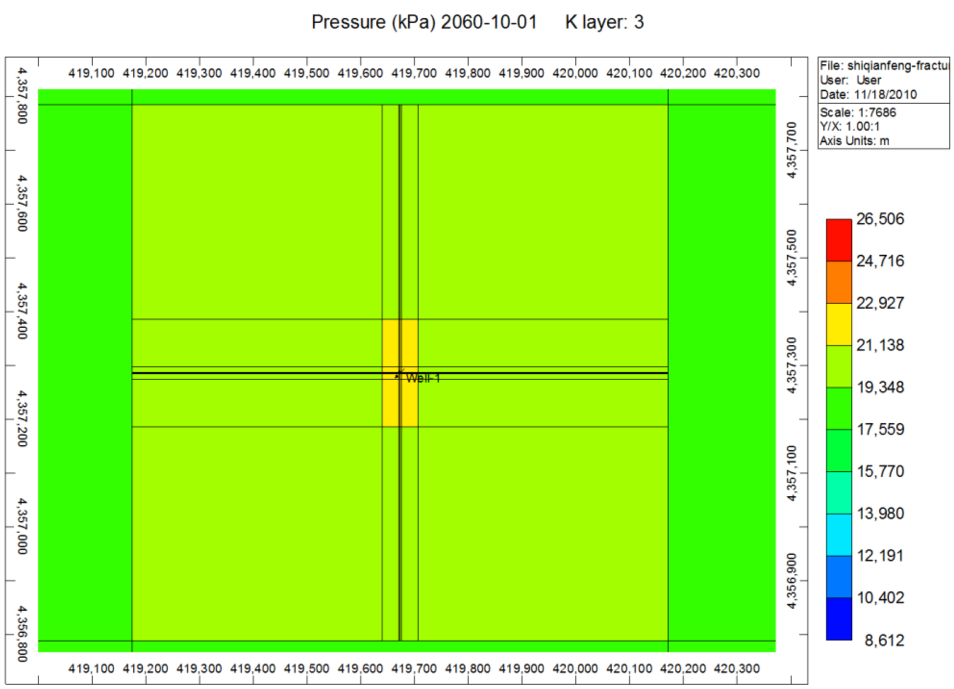

Figure 3.3.10. Distribution of the pressure perturbation in Shiqianfeng Group using revised parameters after injection for 50 years. Perturbation has reached the lateral limits of the model.

Case3: One horizontal well; with hydraulic fracturing

A horizontal well in the Shiqianfeng layer was introduced into the simulation to determine the degree injection rate of CO_2 could be improved. With one horizontal well with hydraulic fracturing, CO_2 injection can be increased in the Shiqianfeng layer by an order of magnitude. The greatest amount that could be injected into a single well is approximately 25% of the Shenhua project target of 0.1Mt/yr. It appears that multiple wells or laterals will be required. However, this is highly dependent on reservoir parameters that are not well defined at this time. Well testing is required. It also appears that operational interference between multiple injection wells will require spacing beyond the 2,000 meters used in the model.

Case3: One horizontal well; with hydraulic fracturing

Horizontal well settings are as follow:

Drilling length=300m*5 stages=1500m

Fracture width=0.0025m

Half- length=150m

Fracture orientation=J

Permeability in fracture=410md

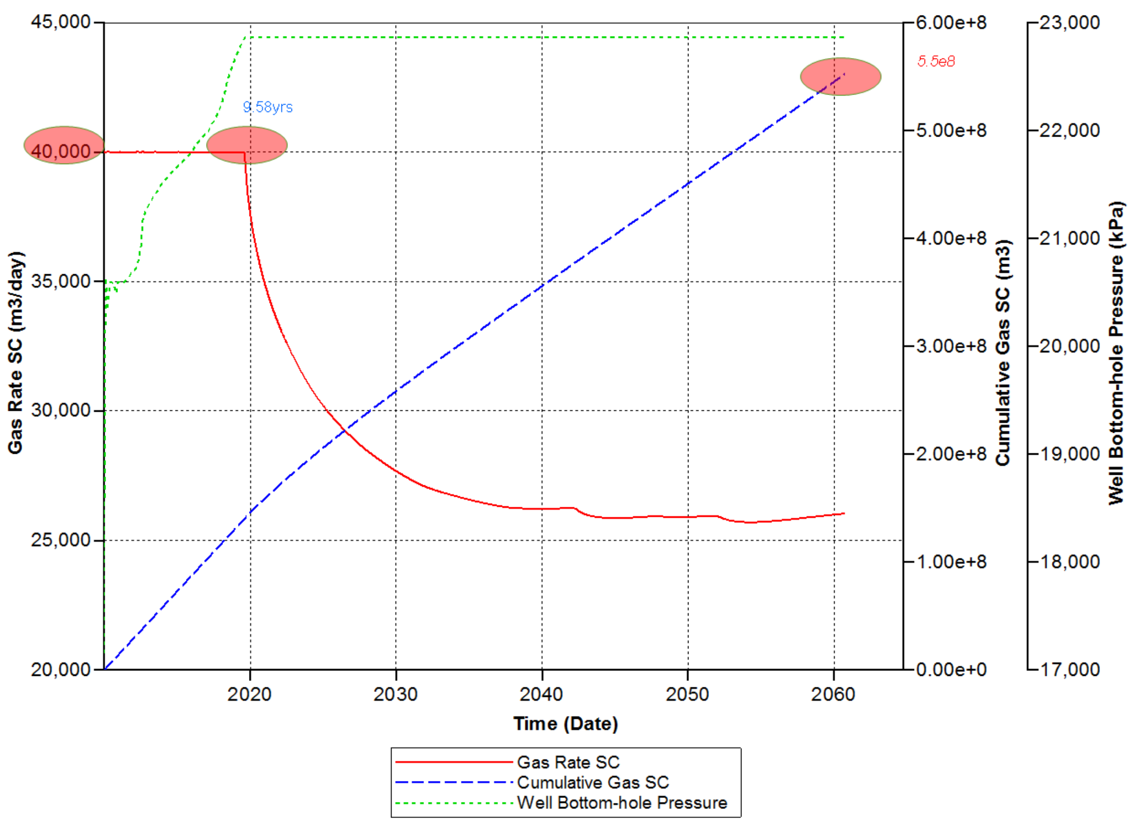

Figure 3.3.11, Results of simulation case 3 Shiqianfeng Group. **<u>Shiqianfeng Group</u>**

If the injection rate is 40,000m^3/day, the stable injection just last for 9.58 yrs, the cumulative injection can be 5.5e8 m^3 which is 23,975 tons/year. Horizontal well drilling and hydraulic fracturing significantly increase the injection quantities. However, the model is severally influenced by the elevated CO_2 concentration and pressure perturbation reaching the no flow boundaries of the model (Figures 3.3.12, 3.3.13).

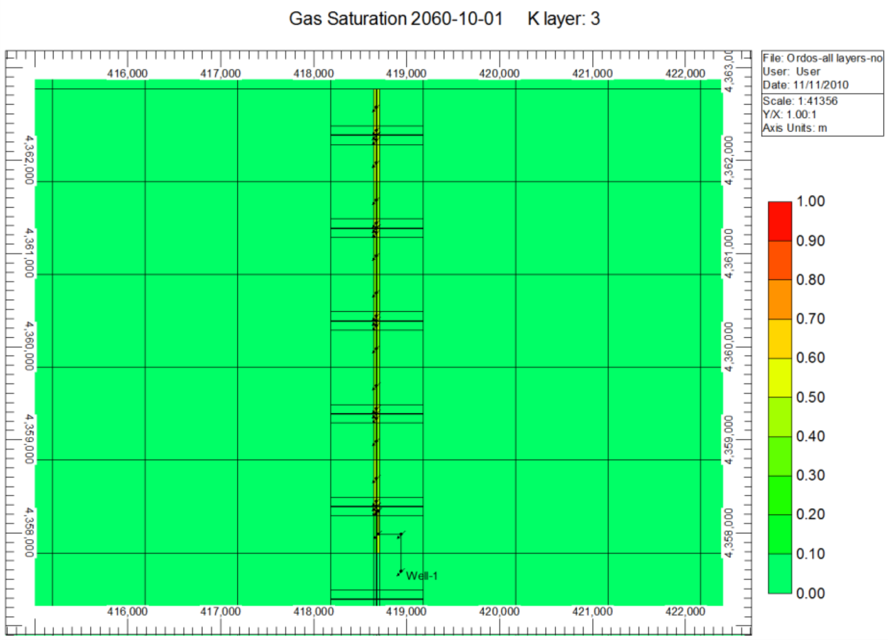

Figure 3.3.12. Distribution of CO_2 saturation in the Shiqianfeng Group using revised parameters and introducing horizontal drilling after injection for 50 years.

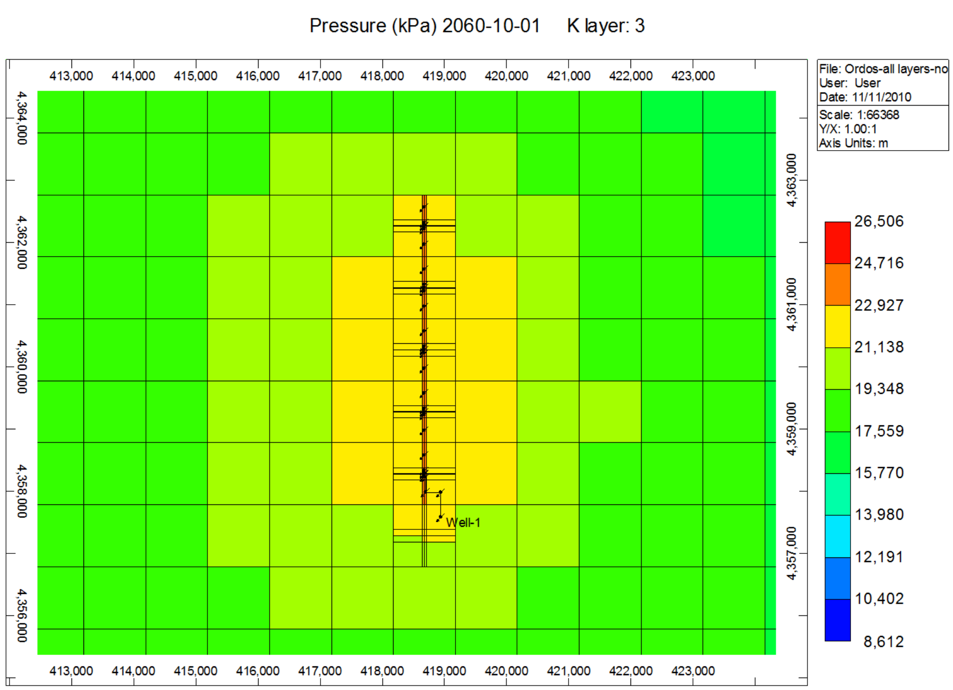

Figure 3.3.13. Distribution of the pressure perturbation in Shiqianfeng Group using revised parameters after injection for 50 years. Perturbation has reached the lateral limits of the model.

Suggestions for Future Work include:

1) Better define the reservoir parameters used in constructing the layers of the geomodel. This can be undertaken by incorporating the 3D seismic data, core data, log data and pressure testing.
2) Expand the model size to eliminate the artificial effects of no-flow boundaries.
3) Incorporate residual trapping which will require capillary pressure and relative permeability testing.
4) Incorporate geochemical data to investigate chemical trapping and potential changes in permeability/porosity.

Subtask 3.4. – Evaluate Selected Deep Unmineable Coal Seams.

Approach

Collect preliminary data to design a plan for initial evaluation of deep unmineable coal seams.

Results and Discussion

Task Complete

Task 4 – Large Scale Sequestration Assessment

Subtask 4.1. – Geological overview

Approach

The subtask will result in a database for the Ordos Basin that can be used to identify sequestration sites for a spatial model. This model can be used to assess the economic costs for of sequestration for the variety of coal conversion plants that have been developed in the Ordos Basin.

Results and Discussion

This task concentrated on understanding and extending the CCS simulator model developed by Los Alamos National Laboratory using US data and information. The initial model parameters and data requirements were outlined, then the next step was to adapt the model to the Ordos Basin in China to look at the options for storing CO2 from multiple coal conversion plants in appropriate sinks at minimum cost. The model was extended to a joint production model, integrating production of CO2 with the production of the firm. The intent of this model is to connect CO_2 sources and sinks with least cost pipeline networks by considering both geographic and demographic factors including population, slope, distance, and existing pipeline right of ways.

In order to implement a large-scale CCUS program an infrastructure needs to be designed and costs must be assessed. The infrastructure requires careful consideration of a pipeline network, which includes potential pipeline routes to connect CO_2 sources and reservoirs. The types of costs associated with the program include those for capturing, compressing, transporting, and injecting CO_2. In this work, an optimization model for a comprehensive CCUS network which will simultaneously estimate input and output costs, source and reservoir locations, and possible pipeline routes to be connected was designed. This comprehensive CCUS network model is sensitive to potential changes in costs; quantities of CO_2 transported and stored, and network utilization. This comprehensive planning will help scientists, stakeholders, and policy makers make informed decisions regarding a large-scale CCUS program.

Model Description

This research will continue to expand upon the *SimCCUS* model, developed by Los Alamos National Laboratory, by incorporating a carbon price into a temporal model, allowing for an improved understanding of the minimum cost CCUS network over time and the sensitivity of costs to different carbon prices. Economic analysis includes an examination of the marginal costs of abatement for firms, including the marginal costs of capture, transport, and storage for multiple production facilities under a range of carbon prices.

In addition, a joint production model of CO_2 with a firm's output in conjunction with the *SimCCUS* network has been designed. The differences between a series of static models and a truly adaptive temporal model has been highlighted. A joint production model more accurately reflects the true scenario faced by firms, where production at multiple facilities must be balanced with the costs of waste products versus the foregone revenue from reduced production. This research focused on price uncertainty in outputs by varying both the output and carbon prices through a range of scenarios; this allows comparison of carbon storage and production outcomes for the firm. Additionally, the sensitivity of the amount of carbon stored and the pipeline network solution to changing carbon and output prices was examined. By considering an increased volume of CO_2 to be stored, this joint production model allows for comparison with the temporal model.

The Ordos Basin in Inner Mongolia China was one of the study regions for this research. Geographic information including the location of CO_2 sources, sinks and potential pipeline routes that connect them are an important input in this research. CO_2 exhaust streams from coal-to-liquids and coal-to-chemicals plants will also be used as inputs for these models.

The first temporal price models are complete, and joint production models are in development. When finished, these models will show how a regional CCUS network operates over time in the Ordos Basin, and compare the costs of sequestration and storage to revenues gained from the sale of final products.

A comprehensive regional model of the Ordos basin that connects potential CO_2 sources and sinks with a pipeline model is defined and utilized in this section. This work uses the *SimCCS* to model the regional CCS network in the Ordos basin. *SimCCS* considers seven interdependent decisions required for a comprehensive CCS optimization model (Middleton and Bielicki 2009; Keating, Middleton et al. 2011; Kuby, Bielicki et al. 2011; Middleton, Kuby et al. 2012). These seven decisions include:

How much CO_2 to capture,

- From which potential sources,
- Where and when to construct pipelines,
- What size pipelines,
- Which reservoirs should be chosen for CO_2 storage,
- How much CO_2 to inject in each reservoir,
- How to distribute the CO_2 from spatially dispersed sources, through the network to the reservoirs for storage.

By choosing a price of CO_2 emission, each firm in the model compares the costs of capture, transport, and storage to the costs incurred by just emitting the CO_2. If it is cheaper to emit the CO_2, instead of engaging in CCUS, then the firm will emit. A simpler model that chooses a cap on total CO_2 emissions in a region can also be performed.

The Ordos basin contains a mix of CO_2 emitting industries, including traditional coal power plants, iron and steel foundries, synthetic ammonia factories, and various coal-to-liquids facilities. All of these industries are potential targets for CCUS in the near future, with the coal-to-liquids facilities likely the leading candidates due to their relatively lower cost to capture CO_2. The cost to capture is low because of the nature of the chemical process utilized in the CTL industry currently emits high purity streams of CO_2 into the atmosphere. Capturing CO_2 from these high concentration streams is easier and cheaper than capturing from low concentration streams like post combustion flue gas from a coal power plant. Nineteen CTL plants in the Ordos basin are used in the *SimCCS* model.

Due to low information about the nature of the sources in the Ordos basin, as well as to the level of technology employed in each facility, assumptions about the costs to capture CO_2, and the amount of CO_2 available to be captured have been made. The cost to capture for CTL plants in the Ordos basin likely varies by facility, but is uniform in the model formulation. This leads to each plant being essentially treated as having an identical cost to capture, but being able to capture differing amounts based upon existing CO_2 emissions.

The conformity in the model inputs leads to some obvious model outcomes, for instance when the potential price of per unit carbon emission is greater than the sum of the per unit costs of capture, transport, and storage, all CTL facilities in the Ordos basin choose to store CO_2. More robust data about the differences in costs between CTL facilities would lead to more interesting outcomes. Additionally, model outcomes are more interesting when multiple types of CO_2 emission sources are included, for instance CTL plants, power plants, and iron and steel refineries with different costs to capture and compress CO_2.

The Ordos basin also contains a mix of geological storage sites that could potentially be used for CCUS. These storage sites are discussed in another section, but they have physical differences in the storage media translate into differing costs to inject and store CO_2. Nine geologic storage sites are used in the *SimCCS* model.

Transporting CO_2 throughout the Ordos basin, from emission source to storage site will most likely entail the building of a robust pipeline network connecting sources and sinks. This pipeline network will require planning and capital investment. The transportation network is based upon a GIS cost surface for the Ordos basin.

The cost surface is an integral part of the *SimCCS* model. The cost surface is used to create a candidate network of pipeline routes connecting sinks and sources. It is a combination of GIS layers to utilize existing land use, slope and aspect, land type, land ownership, population density, and existing pipeline right of ways to attempt to estimate the cost of building any CO_2 pipeline across that parcel.

Some factors (like aspect and slope) will affect construction costs but not right-of-way costs. Two cost surfaces are created to account for these situations. Information that affects construction costs is included in the construction cost surface. While information that affects right-of-ways costs is included in the right-of-way cost surface. Both cost surfaces consists of 1 sq km grid cells, with eight possible routes through each cell. Costs of crossing the cell depend on where the candidate network enters each cell, and where it leaves. The cost associated with each type of category in the various GIS layers is based upon expert opinion in the field, and general consensus.

The candidate pipeline network is the based upon the spatial location of the associated CO_2 sources and sinks. The combination of all interconnecting sources, all interconnecting sinks, and all sinks and sources interconnecting leads to a heavily redundant candidate network. The network is trimmed of pipeline routes of equal cost in order to reduce the complexity of the problem.

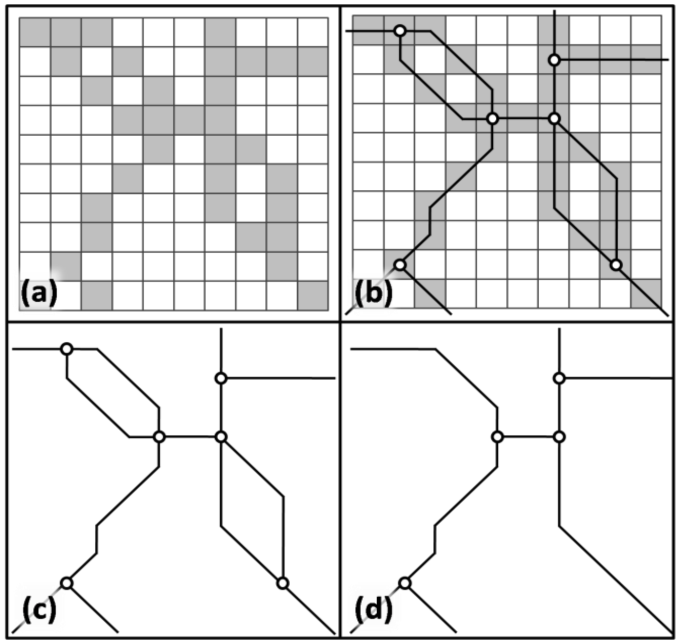

Figure 4.1.1: a) shows how a GIS based raster cost surface displays pipeline routes. b) overlays a vector pipeline network based on the raster paths. c) shows the extraction of the vector potential pipeline network. d) displays a pipeline network trimmed of duplicate routes of equal cost. (Middleton, Kuby et al. 2012)

SimCCS combines information about the costs to capture, transport, and store CO_2 from each potential source to each potential sink in the study area.

Results

Figure 4.1.2 displays a snapshot of one *SimCCS* time period solution. The red cylinders are the CO_2 sources, coal to liquids plants in the Ordos basin. The diameter of the cylinder represents the potential yearly capturable CO_2 emission from the plant. The height of the cylinder represents the cost associated with capturing the CO_2. The darker red segment of the cylinder represents the amount of CO_2 that is actually captured during this period.

The blue cylinders represent the CO_2 sinks. The diameter of the cylinder represents the potential yearly storage of CO_2 in the sink. The height of the cylinder represents the cost associated with storing the CO_2. The darker blue segment of the cylinder represents the amount of CO_2 that is actually stored during this period.

The grey lines represent potential pipelines in the network. The green line represents a built and functional CO_2 pipeline, connecting the emitting source to the storage sink. The thickness of the green line represents the diameter of the pipeline, which depends on the amount of CO_2 forecast to flow through it. A potential enhancement to this model is the dynamic *SimCCS* model, which will forecast future transportation flows that are larger than present flows, and will overbuild pipeline capacity in earlier time periods to anticipate cost savings in future periods.

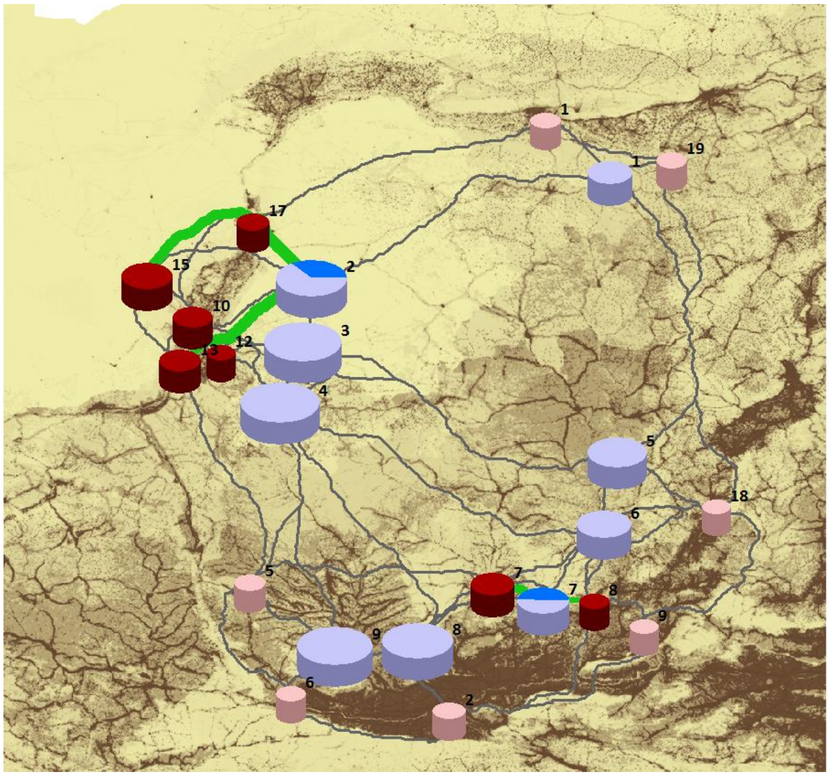

Figure 4.1.2 shows a *SimCCS* output showing the CO_2 storage network at an emission price of \$22 /tCO_2. No plants choose to capture and store below a price of \$22 /tCO_2.

All CTL plants have a \$20 /tCO_2 cost to capture. Not every plant chooses to capture and store because of the additional costs associated with transport and storage of a large volume of CO_2. This scenario captures and stores 46.296 Mt CO_2 out of a total possible 59.772 MT CO_2 at a total cost of \$756.79 million USD. There is an additional charge of \$22/tCO_2 time the amount of CO_2 not captured and stored. This amount is \$296.43 million USD. Together this provides a unit cost of the full CCUS network of \$17.62 /tCO_2.

The pipeline network length extends for 665 km and connects 10 CO_2 sources with 2 storage sites. Not all CO_2 sources are visible due to the close proximity of some of the sources leading them to be considered as one source node. The cost to transport the CO_2 is \$2.09 /tCO_2. The cost to store the CO_2 is \$2.25 /tCO_2. The total cost of capture, transport, storage, and emission of CO_2 not stored is \$24.17 /tCO_2. 13.47 Mt CO_2 are still emitted. Figure X.3 graphs the changes in costs when the price to emit CO_2 increases to \$23 and \$24 /tCO_2. At \$24 /tCO_2 every CTL source in the Ordos basin is storing 90% of their CO_2 emissions. The total pipeline network is 1823 km of pipeline.

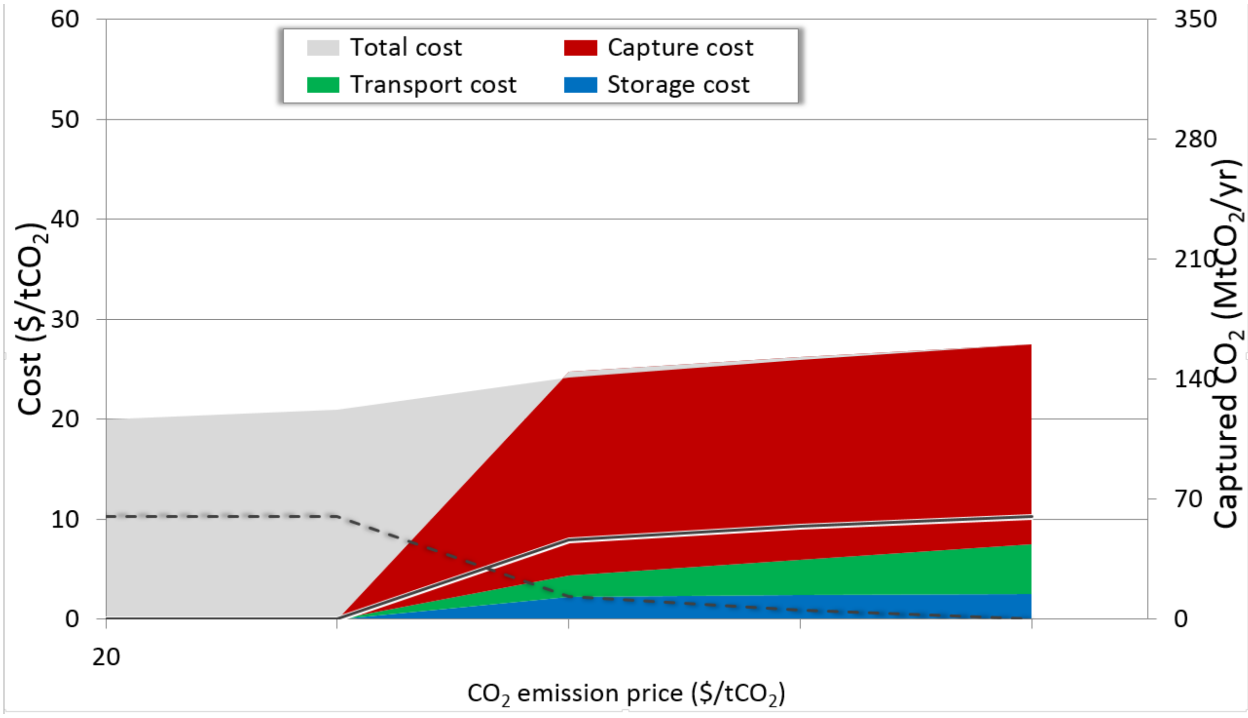

Figure 4.1.3. *SimCCS* solution with carbon price varying from \$20 to \$24 /tCO$_2$

A more interesting solution is when more than just CTL facilities are included in the *SimCCS* run. Different types of CO_2 emitting facilities have different costs to capture CO_2, and the model is more complicated. A preliminary simulation with 80 CO_2 emitting sources grouped into 30km clusters including power plants, refineries, iron and steel foundries, CTL facilities, and even a hydrogen production facility is displayed in Figure 4.1.4.

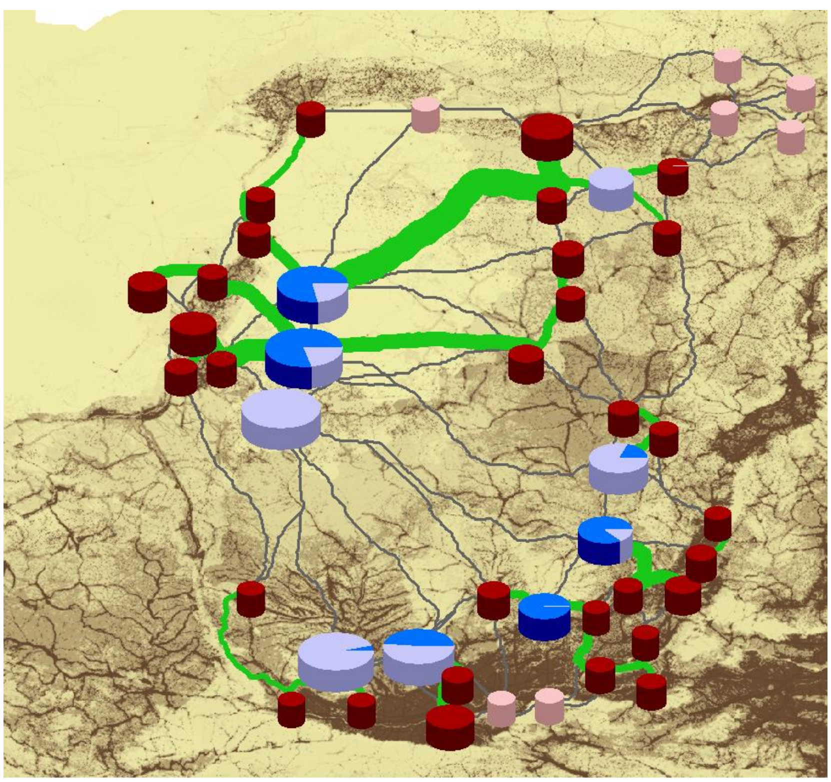

Figure 4.1.4. Carbon price is \$60 /tCO$_2$

At the \$60 /tCO_2 price scenario a variety of different sources all store in the same eight sinks (one is not utilized). This would be a scenario where different industries may be competing for CO_2 storage space in limited storage reservoirs. First mover, and other game theory scenarios may occur where the first firms to capture the right to store may reap the largest benefits. Figure 4.1.5 displays the range of costs in this larger scenario.

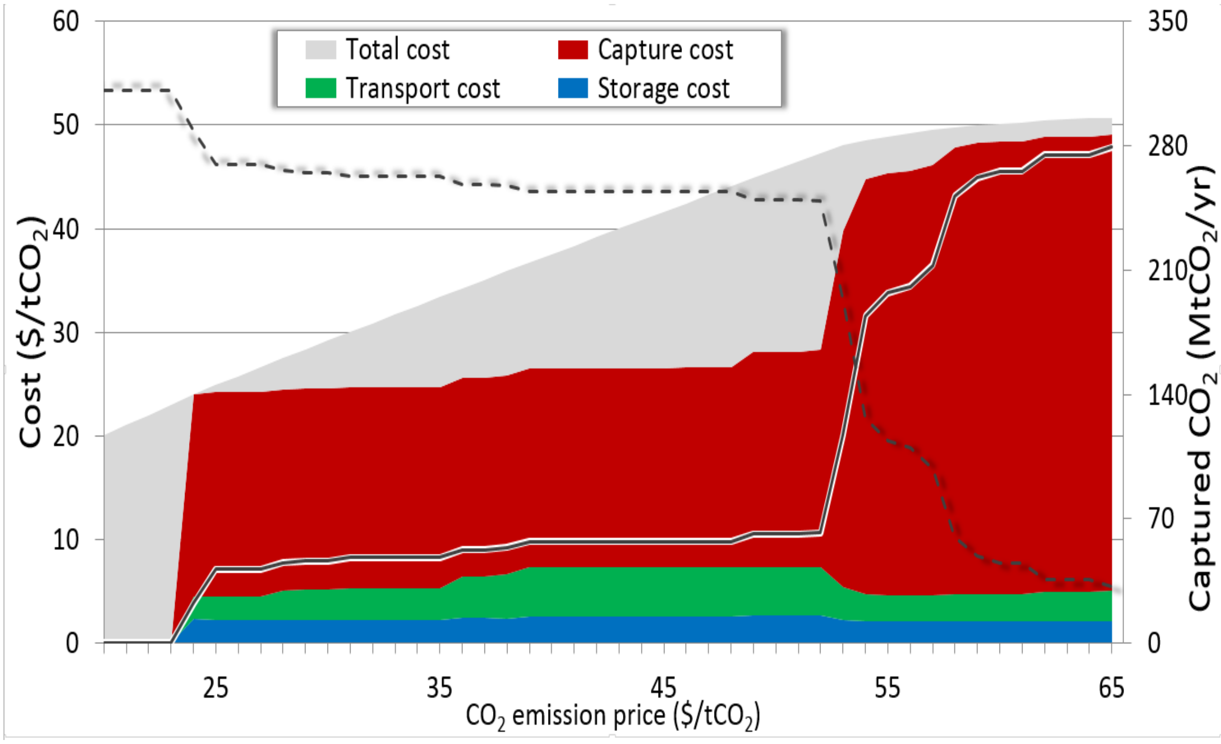

Figure 4.1.5.

References

Keating, G. N., R. S. Middleton, et al. (2011). "Mesoscale Carbon Sequestration Site Screening and CCS Infrastructure Analysis." Environmental Science & Technology **45**(1): 215-222.

Kuby, M. J., J. M. Bielicki, et al. (2011). "Optimal spatial deployment of CO2 capture and storage given a price on carbon." International Regional Science Review **34**: 285-305.

Middleton, R. S. and J. M. Bielicki (2009). "A scalable infrastructure model for carbon capture and storage: SimCCS." Energy Policy **37**: 1052-1060.

Middleton, R. S., M. J. Kuby, et al. (2012). "Generating candidate networks for optimization: the CO2 capture and storage optimization problem." Computers, Environment, and Urban Systems **36**: 18-29.

Subtask 4.2. – Initial Design of Pilot Project

Approach

Potential sequestration sites will provide the spatial basis for storage nodes for the CCS simulation model. The sites will be characterized to the extent of available data on relevant geological properties for storage rates and volumes.

Results and Discussion

Due to time and resource constraints, no activity occurred on this subtask.

Cost Status

	U.S China Carbon Capture and Storage Development Project
Project Title:	at West Virginia University
DOE Award Number:	DE-FE0008344
	Start: 03/01/12 End: 12/31/13

Baseline Reporting Quarter	Q1 (6/30/12)	Q2 (9/31/12)	Q3 (12/31/12)	Q4 (3/31/12)	Q5 (6/30/13)
Baseline Cost Plan	(From 424A, Sec. D)				
(from SF-424A)					
Federal Share	$225,000				
Non-Federal Share	$56,491				
Total Planned (Federal and Non-Federal)	$281,491				
Cumulative Baseline Costs					
Actual Incurred Costs					
Federal Share	$0	0.00	12,421.64	4,820.36	33,343.67
Non-Federal Share	$5,066.38	2,034.60	1,910.15	19,752.19	10,282.59
Total Incurred Costs - Quarterly (Federal and Non-Federal)	$5,066.38	2,034.60	14,331.79	24,572.55	43,626.26
Cumulative Incurred Costs	$5,066.38	7,100.98	21,432.77	46,005.32	89,631.58
Uncosted					
Federal Share	$225,000	225,000	212,578.36	207,758.00	174,414.33
Non-Federal Share	$51,423.62	49,389.02	47,478.87	27,726.68	17,444.09
Total Uncosted - Quarterly (Federal and Non-Federal)	$276,423.62	274,389.02	260,057.23	235,484.68	191,858.42

	U.S China Carbon Capture and Storage Development Project
Project Title:	at West Virginia University
DOE Award Number:	DE-FE0008344

Start: 03/01/12 End: 12/31/13

Baseline Reporting Quarter	Q6 (9/31/13)	Q7 (12/31/13)			
Baseline Cost Plan	(From 424A, Sec. D)				
(from SF-424A)					
Federal Share					
Non-Federal Share					
Total Planned (Federal and Non-Federal)					
Cumulative Baseline Costs					
Actual Incurred Costs					
Federal Share	94,949.64	79,464.69			
Non-Federal Share	2,826.21	41,587.45			
Total Incurred Costs - Quarterly (Federal and Non-Federal)	97,775.85	121,052.14			
Cumulative Incurred Costs	187,407.43	308,459.57			
Uncosted					
Federal Share	79,464.69	0.00			
Non-Federal Share	14,617.88	-26,969.57			
Total Uncosted - Quarterly (Federal and Non-Federal)	94,082.57	-26,969.57			