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CO_2 Interim Storage: Technical Characteristics and Potential Role in CO_2 Market Development

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Abstract

In the absence of legislation that imposes a price on CO_2 emissions, few significant economic incentives currently exist for large-scale commercial application of CO_2 Capture and Storage (CCS). A novel technique, currently under development, shows potential to add value to sequestered CO_2, promote its utilization, and bridge the gap between its supply and demand, thus allowing the development of fully-integrated and reliable CO_2 market. This technique is referred to as "CO_2 Interim Storage", or briefly, CIS. CIS involves storing CO_2 for a finite period of time to be subsequently utilized in CO_2 Enhanced Oil Recovery (EOR) and potentially other industrial processes. The feasibility of CO_2 storage is assessed based on three major variables: the distance between CO_2 source and storage medium, the general trend of CO_2 storage in and delivery from the storage medium (primarily governed by the market dynamics of supply and demand), as well as the frequency of CO_2 injection into and extraction from the storage medium. The importance of CIS as a major tool for CO_2 market and infrastructure development becomes clear upon comparing this new technology to the widely implemented underground natural gas (NG) storage and assessing its role in energy hybridization and in meeting variable and localized CO_2 demand. In this study, the flow of CO_2 in underground storage reservoirs is numerically simulated to provide general analysis of the technical aspects associated with varying CO_2 injection rates. The simulations show that the CO_2 plume and pressure buildup profiles are comparable for constant and variable injection rates. Also, in the cases of variable injection, the pressure variation dampens as injection proceeds with time. In addition, a case-study is conducted in which CIS is implemented to meet the CO_2 demand for EOR operations in the state of Wyoming from CO_2 emissions of in-state coal power plants. This is achieved via modeling an integrated source-sink CO_2 network. The results show that the economic attractiveness of the project is dependent on the availability of CO_2, the distance between CO_2 sources, interim storage sites, and sinks, as well as the price and demand of CO_2 for EOR.

Keywords: CO_2 Interim Storage (CIS); flow modeling; enhanced oil recovey; integrated CO_2 network

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1. Introduction

In the last two decades, the relationship between energy consumption, CO_2 emissions, and global warming has been increasingly investigated by academic institutions, industrial firms, and political organizations to understand its

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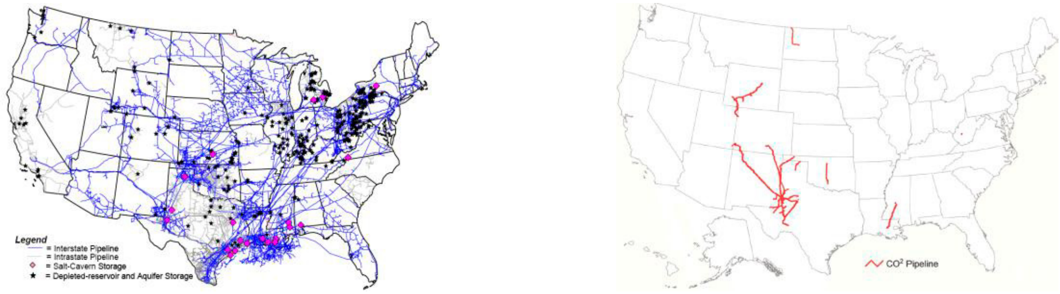
governing principles and potential effects on international businesses and human wellbeing. Among other alternatives, CO_2 Capture and Sequestration (CCS) is one of the most promising solutions to secure energy demand and mitigate climate change, particularly in those parts of the world that are heavily reliant on fossil fuels and do not have other good energy supply options. Today, as the technical challenges and safety concerns associated with CCS are being intensively researched and actively resolved, the lack of economic incentive for large-scale commercial application becomes a major deterrent that need to be addressed. In this regard, an important question that remains to be answered is: What techniques can be used to better match CO_2 supply and demand, steadily and economically, when both supply and demand varies in timing and in scale? A novel technique, currently under development, shows potential to add value to sequestered CO_2, promote its utilization, and bridge the gap between its supply and demand, thus allowing the development of fully-integrated and reliable CO_2 market. This technique is referred to as "CO_2 Interim Storage", or briefly, CIS.

CIS involves storing CO_2 for a finite period of time to be subsequently utilized in CO_2-EOR and potentially other industrial processes. Captured and compressed, CO_2 is transported in pipelines to subsurface interim-storage geologic formations, primarily deep saline aquifers and depleted oil and gas reservoirs. The feasibility of CO_2 storage is assessed based on three major variables: the distance between CO_2 source and storage medium, the general trend of CO_2 storage in and delivery from the storage medium (based on the market variability and dynamics of supply and demand), as well as the frequency of CO_2 injection into and extraction from the storage medium. Before examining some of the theoretical, physical, and practical aspects of CIS, it is crucial to identify the major motives behind its deployment. The importance of CIS as a major tool for the CO_2 market and infrastructure development becomes clear upon comparing this new technology to the widely implemented natural gas underground storage and assessing its role in matching localized and variable CO_2 supply and demand.

2. CIS: A Tool for CO_2 Market Development

2.1 Natural Gas Interim Storage: Similar Approach

Remarkable similarities exist between natural gas storage and CIS at the level of storage capacity and mechanisms, transportation infrastructure, spatial distribution of sources and sinks, and market dynamics. In 2007, 400 sites for underground natural gas storage existed in the US, including 326 depleted oil and gas reservoirs, 43 deep saline aquifers, and 31 salt-dome formation. The total storage capacity was estimated to be 8,402,216 million cubic feet (MMcf), including: 6,801,291 MMcf (81%) in saline aquifers, 1,347,516 MMcf (16%) in depleted oil and gas reservoirs, and 253,410 MMcf (3%) in salt caverns [1]. In this regard, the same type of storage sites used for NG can be used for storing CO_2. The geological features needed to store both fluids are basically the same: high storage volume (permeable reservoir) and the presence of a geologic barrier that prevents leakage (cap rock).



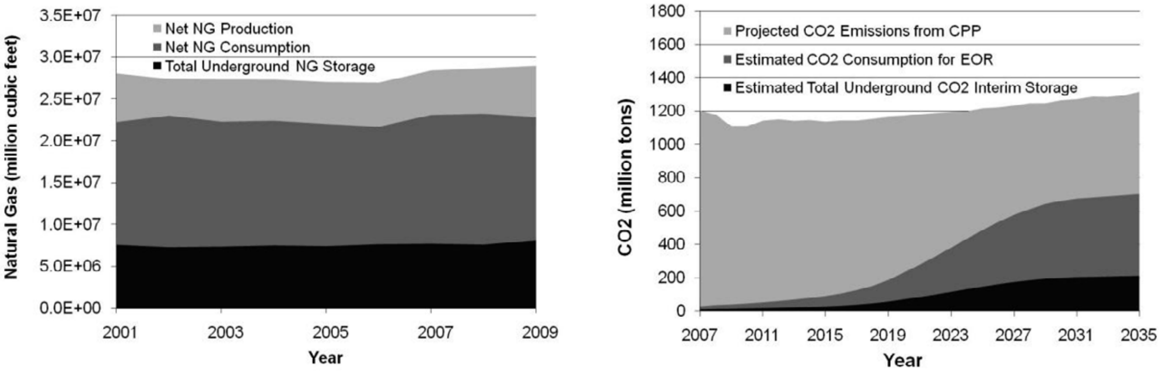
(a) (b)

Figure 1. NG pipeline network (a) [2] and CO_2 pipeline network (b) [3] in the US

In addition to the significant storage capacity, a well established NG network extends across the US with approximately 300,000 miles of pipelines for the transportation of this important fuel [4]. Two main factors have dictated the layout of this network, namely, the spatial match between available production points, storage sites, and markets, and the variability of demand with respect to time. Following the same rationale, an equivalent network of

CO_2 pipelines across the US can be developed based on the same factors. In fact, the prospective CO_2 network can be argued to be in close proximity to the currently existing NG network. This is due to the fact that many of the NG consumption focal points can be thought of as being potential CO_2 sources or in close proximity to potential CO_2 sources (industrial areas, power plants…etc). Equally important, the geological storage sites of NG and CO_2 have the same features, and thus can be located close to each others. Figure 1 shows the current NG and CO_2 pipeline networks in the US. Clearly, significant opportunities still exist for extending the CO_2 network across the states.

The need for NG as a major fuel and its commercial value as a commodity is the primary incentive behind developing its extensive transportation network. As such, an equivalent economic incentive is needed for an integrated CO_2 network to be found. Today, and in the absence of carbon tax or carbon credits, the economic value of CO_2 is primarily due to its use in enhanced oil recovery and few other industrial processes. According to the National Energy Technology Lab (NETL), the total amount of economically recoverable oil reserves in the US by state-of-art EOR operations is approximately 45 billion barrels. This would require a total of 11.7-14.4 billion metric tons of CO_2. Taking into account that only 237,000 bbl/day of oil were produced by CO_2-EOR in the US in 2006, a huge potential exist for developing a CO_2 market for enhanced oil recovery [5]. In the last decade, NG annual production and consumption in the US fluctuated around 27,500 and 22,500 billion cubic feet, respectively [6,7]. On average, NG underground storage was equivalent to one-third of the overall consumption [1]. By analogy, CO_2 emissions that can be captured from stationary sources, specifically coal power plants (CPP), can be thought of as the overall CO_2 "production", and the CO_2 needed for EOR can be treated as CO_2 "consumption". Assuming that oil production will continue till 2050 [8], the use of CO_2 in EOR can be expected to grow significantly beyond 2020 (due to increasing oil prices) to peak around 2035, before decreasing again due to overall decline in oil production. Also, by analogy to NG, one-third of the annual CO_2 consumption in EOR may presumably to be stored underground for later use. Based on the projections of CO_2 emissions from CPP provided by the US Energy Information Administration (EIA), a general trend for the deployment and capacity of CIS in the US can be predicted [9]. By 2035, the CO_2 consumption for EOR increases to almost 700,000 Mt/yr, allowing the recovery of around 30 billion barrels of oil in total. This is illustrated in Figure 2 below.



(a) (b)

Figure 2. NG market (a) and CO_2 market potential (b) in the US

2.2 Demand Variation: Localized CO_2 Demand for Enhanced Oil Recovery

The first use for CIS is when there is variation in the scale and timing of a demand source, compared to the supply source. For example, demand might vary over time, and be made of a number of small facilities, while supply might be constant and at large scale. The most commonly cited source of CO_2 demand is enhanced oil recovery. Many thousands of small, local, and dispersed depleted oil fields exist in the US, many of which can be potential candidates for CO_2-EOR. The economics of injecting CO_2 for enhanced oil recovery in these fields is primarily governed by the cost of CO_2 supply, including the cost of transportation. According to a study by McCoy and Ruben, the total pipeline construction cost can be divided into four main categories: materials, labour, right-of-way, and services. Pipeline length and design capacity are two important factors that affect CO_2 pipeline construction and thus overall transportation cost. In this regard, this study shows that decreasing the design capacity of a 100 km CO_2 pipeline constructed in the US Midwest from 10 million tons to 5, 2, and 1 million tons increases the CO_2 transportation cost by a factor of approximately 1.5, 2.5, and 4.5, respectively. Similar results are obtained for the other regions and different pipeline lengths [10]. Taking into account the relatively small and sometimes variable amount of CO_2 needed, oil production rate, and eventually additional oil recovery, the capital cost required for constructing the CO_2 pipeline network for small and dispersed depleted oil fields is generally high enough to make the project economically unfavourable. As such, the presence of localized CIS sites nearby small depleted oil fields helps to reduce transportation expenses, which in turns allows sequestering additional amounts of CO_2 underground through EOR while generating revenue. As an example, Figure 3 shows the distribution of more than 800 oil and gas fields in the State of Wyoming, most of which have less than 1 million tons of CO_2 storage capacity [11]; while CO_2-EOR can be applied to the larger fields, smaller dispersed fields can be used as CIS sites. This will be further discussed in the case study investigated later in the paper.

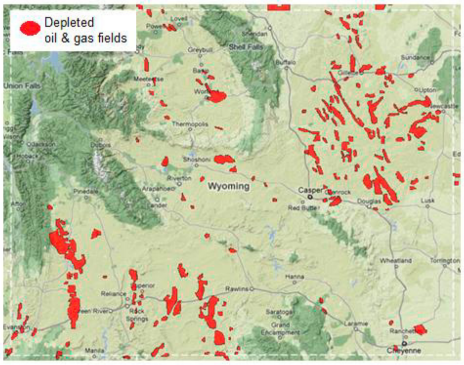


Figure 3. Oil and gas fields in Wyoming [11]

2.3 *Supply Variation: Energy Hybridization*

The second justification for the use of CIS is variability in the scale and timing of CO2 supply in comparison to the demand rates. For example, CO2 could be captured at an intermittent rate, depending on the electricity price variation over the course of days or weeks [12]. Alternatively, intermittent capture might be induced by “hybridized” energy systems. Energy hybridization, which involves integrating fossil fuels and renewable energy sources to generate power, is becoming increasingly more valuable in bridging the gap between conventional and next-generation energy supplies. One example of energy hybridization is generating electricity from an integrated facility that includes a CCS-retrofitted coal power plant and a wind farm. This “energy park” can have a pre-assigned generation capacity and can be directly connected to the grid. If only a fraction of the CO_2 emissions need to be capture from the coal plant, the capture units may not to be run continuously; their operation can be manipulated and optimized. When wind speed is low, all thermal energy generated by the coal plant is used to generate electricity, and the capture units are shut down. However, when wind speed is high, both wind turbines and the coal plant generate electricity. If the overall plant and wind farm power capacity exceeds the utility’s need or the cap on the amount of electricity that can be transmitted to the grid, the excess in the plant’s thermal energy (that is used to produce electricity) can then be used to run the CO_2 capture units. As such, the amount of captured CO_2 depends on the wind power supply and varies based on wind availability. Wind capacity varies significantly both spatially and temporally, which makes the captured CO_2 stream unsteady and inappropriate for EOR applications. In broader terms, this example illustrates that capturing CO_2 from hybrid energy systems involving renewable energy sources (especially wind and solar) may lead to variable CO_2 supply, which cannot be directly used for EOR. In this case, the CIS sites serve as an intermediate step that “smoothes” the variability associated with the CO_2 input from the power facility and delivers a constant steady CO_2 supply to the CO_2-EOR fields. This aspect will also be further explored in the case study investigated later in the paper.

3. Methodology

CIS is a new step in the CCS chain that needs to be assessed. In this regard, investigating the potentials of the CIS technology involves researching two important aspects: storage characterization and modelling, and integrated network modelling. This is illustrated in Figure 4 below. Storage characterization and modelling involves studying different storage formations (saline aquifers, depleted oil and gas fields, and salt caverns), reservoir characteristics (pressure buildup and plume migration), and CO_2 injection and extraction modes (periodic, constant, and monotonically increasing/decreasing). Integrated network modelling, on the other hand, involves performing infrastructure design and economic assessment, optimizing network models, and allocating and characterizing CO_2 point sources (coal power plants), CIS sites, pipeline routes, and EOR fields.

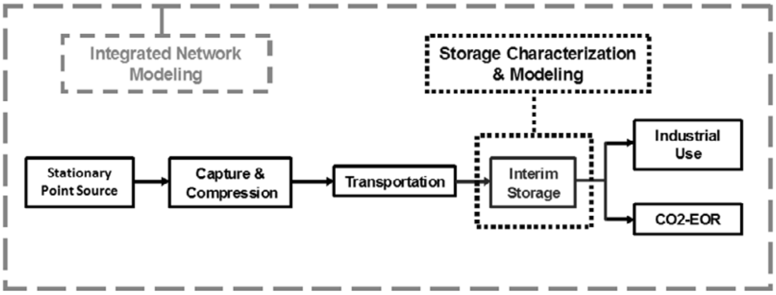


Figure 4. CCS flow diagram with CIS

4. Storage Modeling: Variable CO_2 Injection in Saline Aquifers

4.1 Simulation Setup and Procedure

As mentioned before, the CO_2 supply to the CIS site might be variable. To investigate this phenomenon and its effect on the reservoir behavior, multiphase flow simulator TOUGH2 is used to simulate the injection of CO_2 into a saline aquifer. Three cases are considered: constant injection in radially-confined saline aquifer (case 1), variable injection in radially-confined saline aquifer (case 2), and variable injection in radially-unconfined saline aquifer (case 3). Figure 5 shows the variable CO_2 injection rates in cases 2 and 3. CO_2 is injected for 20 years, at annual rate of 5 Mt/yr. The confined saline aquifer is simulated to have a radius of 10 km while the unconfined saline aquifer is simulated with a 100 km radius. In both cases, the reservoir thickness is 70 m and the seal thickness is 30 m. A radial axisymmetric grid is used to simulate the aquifer, as illustrated in Figure 6. The reservoir porosity, permeability and salinity are assumed to be uniform at 25%, 300 md, and 0.1 wt%, respectively. Similarly, the seal porosity, permeability, and salinity are also assumed to be uniform at 10%, 10 nd, and 0.1% wt, respectively.

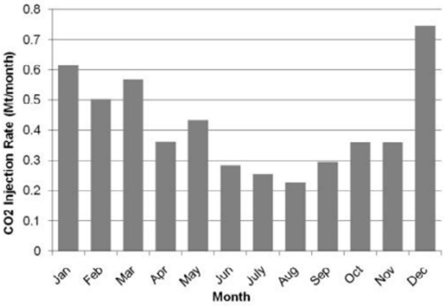


Figure 5. Variable CO_2 injection rates (case 2 and case 3)

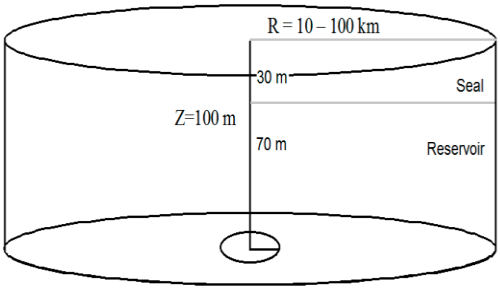


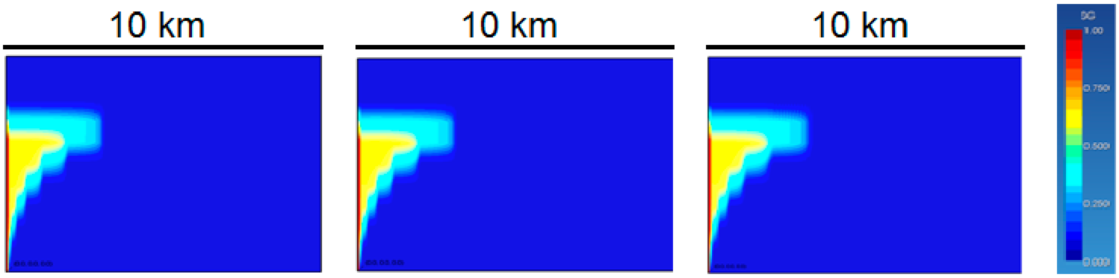
Figure 6. Radial axisymmetric grid of the saline aquifer

4.2 Results and Discussions

The CO_2 profiles in the saline aquifer for the three investigated cases are illustrated in Figure 7 above. As can be noticed, the CO_2 plumes for the three cases are very comparable, which also proved to be the case for overall CO_2 injection rate of 2 Mt/yr and 10 Mt/yr. This suggests that the extent of CO_2 migration in the reservoir is not dependent on injection rate variability or the extent of confinement of the storage medium, and thus the physical phenomena governing CO_2 migration in CIS sites are similar to those of permanent storage.

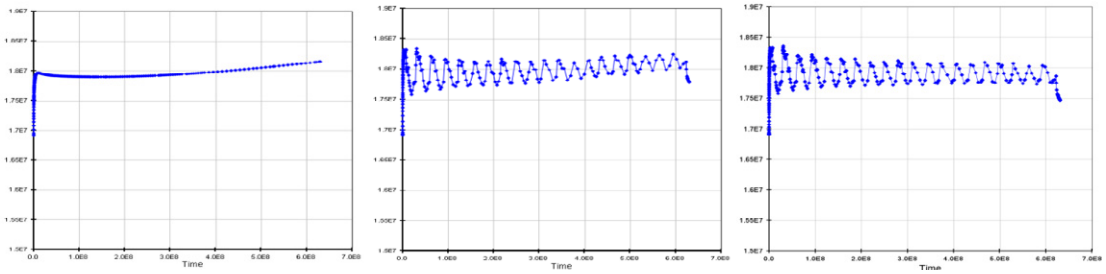
The reservoir pressure buildup profiles for the three aforementioned cases at 100 m and 10 km away from the injection well are illustrated in figures 8 and 9 below, respectively. Near the injection well, the pressure buildup increases with time, steadily in the case of constant injection but periodically in the case of variable injection. This result is reasonable taking into account that the pressure buildup in the reservoir increases with the amount of CO2 injected, and the trend of reservoir pressure variation is directly proportional to that of the CO_2 injection rate. Here, it is important to mention that each pressure "peak" corresponds to pressure variation cycle (analogous to the injection rate variation cycle) over one year. On the other hand, the periodic variations of reservoir pressure due to periodic variations of CO_2 injection rate fades away as the distance from the injection well increases; at 10 km away, the reservoir pressure in all three cases increases almost steadily with time, as illustrated in Figure 9.

Another interesting aspect to note is that in the cases of variable injection near the injection well, the pressure variation cycles (signals) dampen as injection proceeds with time. The decay in amplitude of the pressure signals is attributed to the compressibility of CO_2, which causes the system to be more "flexible" as more CO_2 is injected with time.



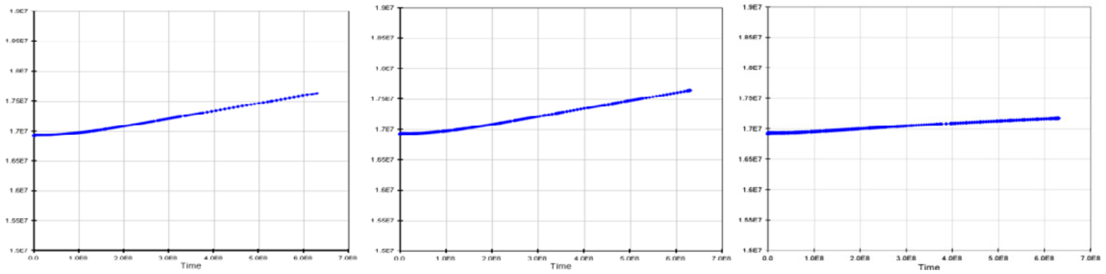
(a) (b) (c)

Figure 7. CO_2 concentration in the saline aquifer of case 1 (a), case 2 (b), and case 3 (c)



(a) (b) (c)

Figure 8. Pressure profile at 100 m away from injection well for case 1 (a), case 2 (b), and case 3 (c)



(a) (b) (c)

Figure 9. Pressure profile at 1o km away from injection well for case 1 (a), case 2 (b), and case 3 (c)

5. Integrated Network Modeling: CO_2 Transportation Network for EOR in Wyoming

5.1 Background

This case study seeks to model CIS to meet the CO_2 demand for Enhanced Oil Recovery operations in the state of Wyoming from CO_2 emissions of in-state coal power plants. This would be achieved via modeling an integrated source-sink CO_2 network, including CIS sites. To emphasize the potential role of CIS in facilitating energy hybridization, the facility is an integrated "energy park" that includes a CCS-retrofitted coal power plant and a wind farm, similar to that described in Section 2.3. The objective of this study is to find the optimal flow-network of CO_2 that is most profitable and cost-effective. This can be thought of as a network optimization problem. Also, since the primary focus of this study is CO_2 transportation from the power plants to the interim storage sites, and from the storage sites to the EOR fields, the optimization program is a network model. The goal is to minimize the total cost (k$/day) of capturing CO_2 from power plants and building the CO_2 pipeline infrastructure between the power plants, CIS sites, and CO_2-EOR sites. Revenue, generated from selling CO_2 to EOR fields, is deducted from the overall cost.

5.2 Model Structure

A number of major assumptions affect the model behavior. To start with, the largest six CPP in the State of Wyoming are considered in this study, along with seven sites identified as appropriate for CIS, the currently operating four CO_2-EOR sites [13], and a wind farm with an overall power capacity equal to approximately 15% that of the coal power plants. The overall CO_2 emissions from the CPP, the CO_2 consumption in EOR fields, and CIS sites storage capacities are 40.7 $MtCO_2$/yr, 2.22 $MtCO_2$/yr, and 62.4 $MtCO_2$, respectively. Upon fulfilling the need of all EOR fields for CO_2, the excess of captured CO_2 remains stored in the CIS sites. An amine-based CO_2 capture system is assumed to be retrofitted to each of the power plants. The capital and operation costs of these systems, estimated by using the IECM model [14], are considered a part of the overall cost in this analysis. Additionally, one set of wind speeds in Wyoming was obtained from NETL and assumed to be representative for the whole state [15]. Due to severe variations with time, the wind power is averaged over a period of one month, and each of the resulting values is assumed to be representative of the daily wind capacity for the whole month. Also, to simplify the model, the electricity demand was assumed to be equal to the CPP baseload and constant throughout the year. In terms of costs, the cost of CO_2 transportation is assumed to be \$3.5/$ktCO_2$.km [10], and the price of CO_2 for EOR is assumed to be fixed at \$30/tCO_2 [5]. The objective function represents the cost of CO_2 capture from coal power plants, calculated by deducting the CO_2-EOR sales revenue from the capture and transportation costs. If the value of the objective function is found to be negative, then a net profit is achieved. Mathematically, this can be represented as:

$$f(x,y) = c_s \sum_i \sum_j x_{i,j} d_{i,j} + c_s \sum_j \sum_k y_{j,k} d_{j,k} + c_c \sum_i \sum_j x_{i,j} - p \sum_j \sum_k y_{j,k} \quad (1)$$

Such that:

$i \in \{\text{set of power plants}\}$; $j \in \{\text{set of CIS sites}\}$; $k \in \{\text{set of EOR fields}\}$

$x_{i,j}$ = the amount of CO_2 shipped from power plants to CIS sites (ktCO2/day)

$y_{j,k}$ = the amount of CO_2 shipped from CIS sites to EOR fields (ktCO2/day)

$f(x,y)$ = total cost of the system (k\$ / day)

$d_{i,j}$ = distance (km) from power plant (*i*) to CIS site (*j*)

$d_{j,k}$ = distance (km) from CIS site (*j*) to EOR field (*k*)

c_s = cost of CO_2 shipment (k\$/$ktCO_2$.km)

c_c = cost of capturing CO_2 from power plants (k\$/$ktCO_2$.km)

$p \sum_j \sum_k y_{j,k}$ = revenue from selling CO_2 to EOR fields, where *p* is the price of CO_2 (k\$/ktCO2.km)

5.3 Results and Discussions

Twelve optimal networks are generated, corresponding to the twelve monthly-averaged wind data. The results show that more pipeline infrastructure is needed when the wind capacity is higher. This is reasonable; as the available wind capacity increases, more CO_2 is captured from the power plants and transported to CIS sites. Due to the limited capacity of the CIS sites, however, the captured CO_2 from one plant might need to be shipped to more than one storage site. Realistically, only one CO_2 network can exist around the year. As such, all possible CO_2 networks were assessed, and an integrated final network that takes into account the twelve possible scenarios is generated. The integrated CO_2 pipeline network is illustrated in Figure 10 below. Although not all illustrated pipelines will transport CO_2 collectively or at their maximum capacity at every instant throughout the whole year, this model is consistent with the common practices of NG transportation; in the US for example, a significant fraction of the NG pipelines are not used at some time throughout the year.

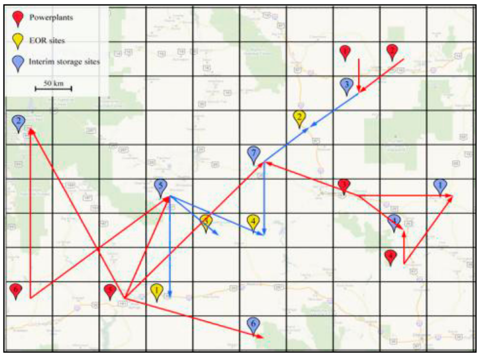


Figure 10. Integrated CO_2 pipeline network in Wyoming

The overall economics of the process are reflected by the value of the objective function. The study results show the cost of CO_2 transportation is directly related to the available wind capacity. As explained before, one interpretation of this observation is that when wind speed is high, both wind turbines and the coal plant generate electricity, and the excess in the plant's thermal energy (that is not used to produce electricity) can then be used to run more CO_2 capture units. The additional CO_2 produced can then be stored in CIS sites and later sold for EOR applications. In some cases, however, wind speed might be very high that more CO_2 might be captured than actually needed for EOR. In that case, more or wider pipelines would be needed to transport CO_2 to farther CIS sites; this contributes to increasing the overall cost. Finally, performing sensitivity analysis shows that, as expected, decreasing the cost of the CO_2 shipment or increasing the price of CO_2 for EOR would make the project more economically attractive.

6. Conclusion

In conclusion, the incentives for investigating CO_2 Interim Storage can be summarized as follows: match CO_2 sources and sinks, add value to captured CO_2 and promote its utilization, and secure CO_2 demand by end-use sectors. Achieving these goals requires researching two important aspects: storage characterization and modelling, and integrated CCS network modelling. In this study, injecting CO_2 in CIS sites at variable rates is investigated and proves to be comparable to constant rate injection. In addition, an integrated source-sink CO_2 network is modelled in which CIS is implemented to meet the CO_2 demand for EOR operations. The results show that the cost of CO_2 transportation is directly related to CO_2 availability and the distance between sources, CIS, and EOR sites.

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