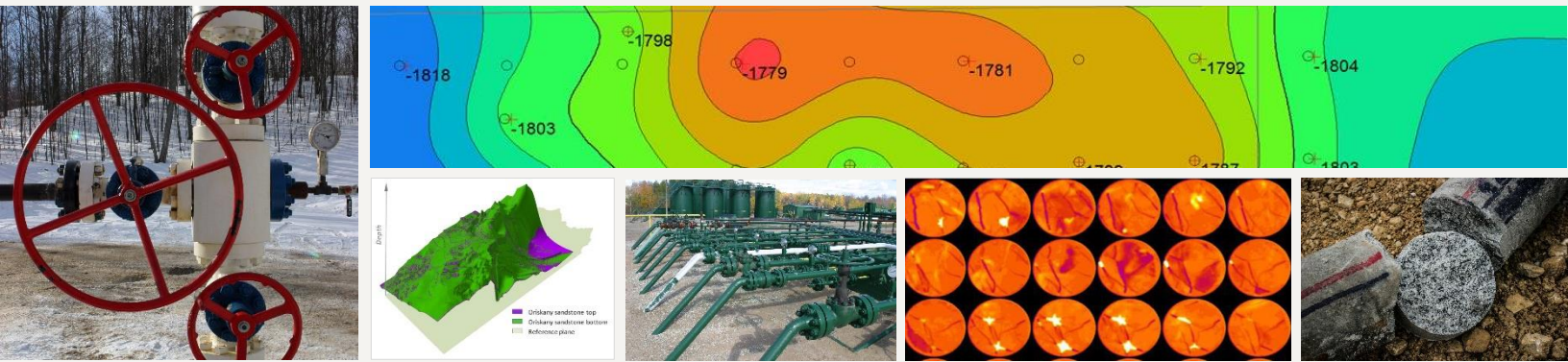




Characterizing the Value of Single Source CO₂ Intermediate Storage (CIS) to Optimize Pipeline Utilization/Economics

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CHARACTERIZING THE VALUE OF SINGLE SOURCE CO₂ INTERMEDIATE STORAGE TO
OPTIMIZE PIPELINE UTILIZATION/ECONOMICS

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ACRONYMS AND ABBREVIATIONS

bbbl	Barrel	\$MM	Million dollars
Bcf	Billion cubic feet	MMscf	Million standard cubic feet
CAPEX	Capital costs	MPa	Megapascal
CCUS	Carbon capture, utilization, and storage	Mt	Million tonnes
CIS	CO ₂ intermediate storage	MW _e	Megawatt electric
CO ₂	Carbon dioxide	N/A	Not applicable/available
CO ₂ _T_COM	FECM/NETL CO ₂ Transport Cost Model	NETL	National Energy Technology Laboratory
d	Day	NGCC	Natural gas combined cycle
DOE	Department of Energy	NPV	Net present value
EIA	U.S. Energy Information Administration	OPEX	Operating costs
EOR	Enhanced oil recovery	PC	Pulverized coal
FE	Fossil energy	SC	Supercritical
FERC	Federal Energy Regulatory Commission	tonne	Metric ton (1,000 kg)
gal	Gallon	UNGS	Underground natural gas storage
IGCC	Integrated gasification combined cycle	U.S.	United States
in	Inch	yr	Year
kg	Kilogram	Year\$	Calendar year (e.g., 2011, 2015) dollars
m	Month	°C	Degrees Celsius
m ³	Cubic meter	°F	Degrees Fahrenheit
mi	Mile	\$/tonne	Dollars per tonne

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EXECUTIVE SUMMARY

One of the main hurdles facing the wide-spread implementation of carbon capture, utilization, and storage (CCUS) is the ability to capture and transport large quantities of carbon dioxide (CO₂) from anthropogenic sources at prices low enough to be competitive with alternative sources of CO₂. Full utilization of CO₂ pipelines is an important strategy to decrease the total cost of utilizing the CO₂ from these sources. Sources with low capture capacity factors and high peak rates of capture can more fully utilize smaller pipelines and provide sustained CO₂ supply to the downstream end-user by incorporating CO₂ intermediate storage (CIS) – sending CO₂ at larger volumes to the intermediate storage reservoirs during periods of peak capture. Then, CO₂ can be produced from intermediate storage during periods of capture or source downtime to continue to fully utilize the smaller diameter pipeline. The feasibility of CIS is determined in this report based on the economic value that maximizing pipeline utilization between CIS and storage represents in the CCUS value chain. This report investigates the economics and details of matching CIS with different CO₂ sources to begin to inform future CCUS discussions about the feasibility of re-production of temporarily stored CO₂. High-level screening of all four types of potential CIS reservoirs [steel tanks, saline aquifers, depleted oil and gas reservoirs, and salt caverns] showed impacts on economic returns for CIS. Multiple withdrawal and injection cycles per year in typical applications and the relatively large capital required only realizes positive economic returns in the current CCUS economic environment for the lowest cost salt cavern CIS reservoirs prominent along the coast of the Gulf of Mexico.

1 INTRODUCTION

Affordable, secure, resilient, and reliable sources of clean energy are required for the continued growth of the domestic U.S. energy market. Carbon capture, utilization, and storage (CCUS) is one of many promising strategies for managing and reducing the anthropogenic emissions of carbon dioxide (CO₂) into the atmosphere from various industries. [1] [2] CCUS involves separating and capturing CO₂ from power-generation and industrial sources, transporting it to a geologic storage site or enhanced oil recovery (EOR) project, and injecting it into a suitable geologic storage or EOR reservoir to isolate it from the atmosphere. [3] Several small- and large-scale CCUS projects are deployed throughout the world and have demonstrated that significant CO₂ emissions reductions are possible; however, the technology is still considered to be emerging in many regards, and CCUS deployment faces challenges in several areas. [4] [5] [6]

Even though there is a business case for CCUS (e.g., reducing CO₂ emissions and capitalizing on CO₂ demand in the oil sector), broader CCUS deployment is hindered by several challenges including cost effectiveness, regulations, and financing. [7] [5] [6] Assessing how to meet stringent federal and state-driven regulations and taking advantage of emerging financial incentives (like the 45Q tax credit) is also a challenge that current and future CCUS site operations face. [8] [9] One concept that could assist in the commercial deployment of CCUS is CO₂ intermediate storage (CIS), which has been studied in scenarios, such as offshore CO₂ injection as a holding (buffer) site after receiving CO₂ by pipeline before the CO₂ is loaded onto ships. [10] [11] CIS is also similar to temporary underground natural gas storage where natural gas is injected and withdrawn from a reservoir based on supply and demand. CIS involves temporarily storing captured CO₂ in reservoirs, such as depleted oil and gas reservoirs, salt caverns, saline aquifers, or above ground steel tanks and reproducing the CO₂ as needed. [12] CIS provides a mechanism for a sustained supply of CO₂ from a source to a downstream end-user; particularly when supply disruptions, such as those observed at Petra Nova and the Boundary Dam project, may occur. [13] [14] A sustained supply of CO₂, buffered by CIS, enables the pipeline between CIS and the downstream end-user to be sized to transport the average annual CO₂ mass capture rate, which is smaller than the maximum CO₂ mass capture rate that unbuffered pipelines must be sized to meet. CIS therefore offers a savings opportunity if the capital and operating costs of CIS is less than the difference between capital and operating costs between pipelines sized for maximum versus (down-sized) average CO₂ mass flow rate. Integration of CIS into CCUS value chains may result in more reliable and less risky business cases, which may facilitate broader CCUS deployment.

This study uses open data sources and NETL-developed resources to determine the economic viability of CIS by determining the break-even pipeline distance between CIS and EOR projects required such that CIS capital costs are offset by reducing the pipeline capital cost with a down-sized pipeline. Generalized relationships are derived to identify the most appropriate CIS type based on the economic advantages CIS offers in each scenario. Modeling the economics of CIS requires an understanding of required reservoir type and capacity and the construction time required for both the CIS reservoir and the associated pipelines.

1.1 VARIABILITY IN CO₂ SOURCES AND FLEXIBLE OPERATION OF CO₂ EOR FIELDS

A plant within the industrial or electric sectors generates CO₂ during operations; however, the CO₂ generated can fluctuate based on the plant's cycle causing potential variability in the CO₂ that can ultimately be captured. This variability in CO₂ generated (and captured) can be approximated by the plant's capacity factor (CF), which is defined as the ratio of a fleet's actual generation to its maximum potential generation. [15] Some smaller industrial point sources, such as ethanol plants, have very high capacity factors (greater than 90%), but multiple ethanol plants may be required to provide an adequate CO₂ supply to a pipeline for a CO₂ EOR project. [16] Larger industrial sources of CO₂ that are capable of providing adequate CO₂ supply, such as electric power plants, tend to have lower average capacity factors of 54 – 55%. [17]

Small CO₂ sources with high capacity factors will have little to no change in diameter of the CO₂ pipeline to transport average rates of CO₂ capture compared to peak capture rates, resulting in no technical or economic benefit of CIS integrated as part of the CCUS value chain. Larger sources of CO₂ with lower capacity factors will require greater amounts of CIS reservoir volume and capital to provide a fixed rate of CO₂ supply. However, lower capacity factor sources will realize a greater pipeline capital and operating cost savings through pipelines sized for a much lower average CO₂ transport rate compared to peak transport rates.

Different sources of CO₂ are likely to have different cycle frequencies. Some sources with high capacity factors are likely to only experience one or two periods of down time per year when no CO₂ is emitted and/or no CO₂ is captured. Other industrial sources, such as natural gas processing plants, have lower capacity factors of around 67% and are likely to experience multiple periods of down time per year. [18] Given the potential variability in both the timing and volume of CO₂ supplies, depending on the source, the geologic conditions for potential CIS reservoirs must be capable of ensuring the necessary containment, injectivity, and deliverability requirements. [19] According to multiple reports, salt domes can be cycled up to twelve times per year compared to once per year for saline aquifers and depleted oil and gas reservoirs. [20] [21] [19] These different cycle times affect which type of CIS can be feasibly matched with different industrial sources. Low capacity factor sources are likely to realize the most economic benefits of CIS and are likely to experience multiple annual cycles. Therefore, the most likely first mover CIS reservoir type are salt caverns.

It is important to note that constant CO₂ supply is not required for economically successful CO₂ EOR operations. Operators of CO₂ EOR fields have implemented various approaches to handling potential CO₂ supply variability. The extent to which the EOR field can accommodate fluctuations in CO₂ supply can be termed as the field's flexibility. Flexible operation of a CO₂ EOR field is common and may suggest a CIS buffered CO₂ supply is not as valuable to the end-user as a buffered natural gas supply. CO₂ EOR field flexibility can be accomplished with a variety of techniques. One way is the use of multiple small modular gas processing units with "phased introduction" at the start of operation. [22] Early CO₂ EOR fields sometimes used a montage technique with daily production and injection data to inform reservoir management staff of patterns where CO₂ flooding parameters required adjustment. [23] Reservoir management can

then be optimized to produce the maximum oil possible with a given input of CO₂. Another way of providing flexible operation of CO₂ EOR fields is the long-term ability to accommodate increasing amounts of returned CO₂ from the production wells. The Wasson Denver Unit, managed by Occidental (Oxy), has a gas processing and recycling plant capable of processing over 200 million standard cubic feet per day (MMscf/d) with an injection capacity of over 400 MMscf/d. [24] In the first year of operation, little returned or recycled CO₂ is utilized, but as the CO₂ flooding matures additional injectors are put online as greater amounts of recycled CO₂ are available (in addition to the “purchased” CO₂). [24] The value proposition of CIS to a CO₂ EOR end-user CCUS value chain, therefore, is not a steady supply of CO₂ to the end-user (although this is a logistical upside that may have some value to end-users in unique situations). Instead, the value proposition is that CIS enables the pipeline between CIS and the end-user to be downsized in diameter, which results in lower pipeline capital and operating expenses.

1.2 TYPES OF CO₂ INTERMEDIATE STORAGE

CIS options vary in desirability due to their unit cost, capacity, deliverability, and cycle time. [25] Not only are the different types of storage characteristics important, but the location of the different storage type is also an important consideration when matching CO₂ sources and sinks. A pipeline to a lower cost type of storage could offset cost advantages of a local more expensive type of storage. The ideal CIS option would have a large CO₂ working gas capacity, low CO₂ base gas capacity, short cycle times, and low total costs. Working gas capacity for CIS refers to the maximum CO₂ volume that can be stored within a storage medium that is available for withdrawal and use. Base gas capacity for CIS refers to the volume of CO₂ that cannot be withdrawn from the CIS reservoir without causing damage to the reservoir. Base gas provides the driving pressure for the withdrawal of working gas. Working gas capacity plus base gas capacity equals the total capacity of a CIS reservoir. A cycle is a progression through one injection period and one withdrawal period. Cycle time is the amount of time (in days) it takes for a CIS to complete one cycle. Cycle rate is the number of cycles that a CIS reservoir can progress through in one year. This report looks at four options for CIS – salt caverns, depleted oil and gas reservoirs, saline aquifers, and steel tanks. Each type has its advantages and disadvantages which are discussed in further detail in the following subsections.

1.2.1 Salt Caverns

Salt caverns are developed in subsurface salt domes or bedded salt formations using a method known as solution-mining. A cavern is created by continuously pumping fresh water into a borehole, which dissolves the salt and turns it into brine water. The brine water is then displaced by more freshwater and then the cycle continues. [26] The majority of salt caverns are located in the Gulf Coast region where salt domes are in abundance. [27] Salt caverns are particularly desirable for flexible gas operations because of their ability to tolerate high deliverability and injection rates and frequent gas cycles. Salt caverns can undergo between 6 to 12 cycles per year compared to depleted oil and gas reservoirs and aquifers, which can only undergo 1 cycle per year. [20] Salt caverns are also highly durable, with respect to geomechanical containment. Their durability can be compared to that of a steel tank since degradation is minimal over time. A unique characteristic of salt caverns is that mineralogical

salt under geologic pressure has the ability to self-heal and seal fractures and potential leakage paths. [28] The biggest disadvantage of a salt cavern is high capital costs. [26] Solution mining costs, and the millions of gallons of brine water produced needs to be treated or disposed of in an environmentally compatible way, are significant cost burdens. When used for natural gas storage, salt caverns require 30% of the cavern's total capacity to be dedicated to base gas. Salt caverns used for CIS are assumed to require a similar base CO₂ percentage. The average size of a salt cavern in the United States has a 2018 working gas volume of 12.8 billion cubic feet [Bcf] according to the U.S. Energy Information Administration (EIA). [29] The cost to develop a salt cavern ranges from \$30MM/Bcf to \$35MM/Bcf of working natural gas capacity when averaged over the entire United States. [19] However, reservoir capital costs for salt cavern storage have been observed as low as \$10MM/Bcf of natural gas storage along the coast of the Gulf of Mexico—the lowest cost out of all CIS options. [20]

Salt caverns are permitted by the Environmental Protection Agency (EPA) Underground Injection Control (UIC) program as Class III during construction. [30] Since no CIS reservoirs have been developed, their operational UIC permit class is debatable. Presumably, CIS operations would fall under Class V, in the experimental technology wells subclass. [31] An argument could be made to permit the injection well as a UIC Class II, since it would be analogous to Class II permitted wells associated with natural gas and oil (e.g., strategic petroleum reserve) intermediate storage. [32] Class II wells are, by definition, associated with hydrocarbons, which CO₂ itself is not. An argument could be made to permit the injection well as UIC Class VI, since Class VI wells are associated with permanent geologic storage of CO₂. [33] Since it is standard procedure to evacuate a salt cavern of its stored contents, and filled with brine prior to abandonment, [34] it is difficult to argue CIS in a salt cavern could be defined as permanent storage.

1.2.2 Depleted Oil and Gas Reservoirs

Depleted oil and gas reservoirs are mature fields with well-defined geological properties where additional hydrocarbon recovery may not be economical. To be a viable storage option, the selected depleted reservoirs must contain a high permeability and porosity so that CO₂ can be effectively injected and withdrawn. [35] The states with the largest amount of total storage capacity of depleted reservoirs include Michigan, followed by Pennsylvania, California, Ohio, and Texas. [19] Depleted oil and gas reservoirs, when used for the intermediate storage of natural gas, are limited to one injection and withdrawal cycle per year and require, on average, a base gas of 50 % of the total reservoir capacity. [19] It is assumed that depleted oil and gas reservoirs would require a similar base CO₂ percentage for CIS. Depleted reservoirs are desirable because 1) they have proven they are geologically capable of containing hydrocarbons for long periods of time, 2) infrastructure on both the surface and subsurface likely already exist, and 3) detailed research has already been done on the structure and characteristics of the reservoir, so additional research is minimal. Due to the existing infrastructure and the minimal effort depleted oil and gas reservoirs take to develop, operate, and maintain, they are typically the least expensive storage option. Depleted gas reservoirs are more desirable than depleted oil reservoirs because depleted gas reservoirs experience less injected gas loss to dissolution in residual oil saturations. [36] The average size of a depleted reservoir in the United States has an

approximate working gas capacity of 12 Bcf in 2018 according to the EIA. [29] The capital cost required to develop a depleted oil or gas reservoir ranges from approximately \$17MM/Bcf to \$20MM/Bcf of working methane gas capacity. [19] Again, costs differ by storage site due to the location, site conditions, and volume of base gas required.

CIS injection wells in depleted oil and gas reservoirs could arguably be permitted as UIC Class II, [32] since they are associated with hydrocarbons, and the base gas that would be permanently stored would be analogous to the CO₂ that is permanently stored in Class II-permitted CO₂ EOR operations. However, Class V experimental technology wells subclass, or Class VI, cannot be ruled out as possible permit classifications. [31] [33]

1.2.3 Aquifers

Aquifers are an underground water-bearing porous rock that can be used as a storage medium for CO₂. Like depleted oil and gas reservoirs, the ideal aquifer for CIS would have a high permeability and porosity while being limited to one injection and production cycle per year [19]. Aquifers are common to the mid-western region of the United States where other storage media are less common. Illinois and Iowa are the leading states, respectively, for the total storage capacity in aquifers. [19] Overall, for both natural gas and CIS, aquifer storage is less desirable than the other storage options because aquifers are more expensive to develop and operate. Unlike depleted oil and gas reservoirs, existing infrastructure does not exist and there is little to no geologic reservoir data available for aquifers. In addition, there is a significant upfront capital loss with an aquifer because only 20% of the total gas injected is available as working gas (the other 80 percent is base gas). [20] [21] [19] On average, a single aquifer storage reservoir located in the United States has a working gas volume around 8.6 Bcf according to 2018 EIA data. [29] Costs range between \$208MM to \$420MM, which is approximately \$21MM/Bcf to \$42MM/Bcf of working natural gas capacity. [19] [37] [38] As a result of the high cost and operational limitations, an aquifer is unlikely to be used for CIS in the near future.

CIS injection wells in aquifers could possibly be permitted as UIC Class V experimental technology wells subclass, or Class VI. [31] [33] It would be difficult to argue for Class II, despite the intermediate storage operational similarities to natural gas intermediate storage in aquifers, since aquifers are not themselves associated with hydrocarbons. [32]

1.2.4 Steel Tanks

The final option for CIS is steel tanks. CO₂ needs to be stored at low temperatures (ideally near the triple point of CO₂ (-52 degrees Celsius [°C] and 0.65 megapascals [MPa]; -62 degrees Fahrenheit [°F] and 94.3 pound-force per square inch [Psi]) in order to have maximum CO₂ density in its liquid form. [39] Liquid CO₂ is typically stored in semi-refrigerated tanks, also known as cryogenic tanks. [40] Since these tanks are usually above ground, they are not location restrictive and can be placed wherever is most economical for the storage operator. Similar to salt caverns, steel tanks offer flexible storage and the ability to alternate between injection and withdrawal more than once per year.

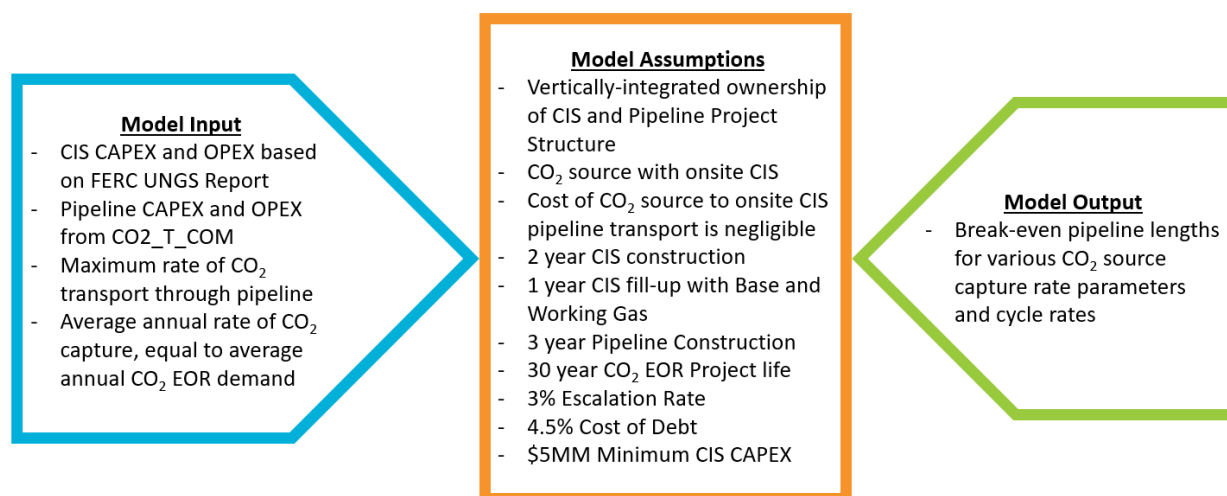
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The disadvantages of using a steel tank as a CIS option is the cost per metric ton (tonne) and the small working capacity (total capacity and working capacity are equal with steel tanks since no base gas is required). For a 15,000 m³ (529,720 cubic feet [ft³]) steel tank, the cost ranges between \$6MM to \$31MM. [43] [44] Tanks have historically been sized from 3,000 m³ (105,944 ft³) to 160,000 m³ (5.65 million ft³). [43] When compared to the price of developing salt cavern storage, the likely maximum size of steel tank storage that would be developed in an area with salt cavern storage available is between 1,700 tonnes and 5,000 tonnes, corresponding to a capital expense of approximately \$5MM, the historical minimum capital expense for salt cavern storage. [26] [29] In geographic areas without formations to create salt caverns, larger steel tank storage is likely since no other CIS options can be cycled multiple times per year. [29] Finally, steel tank storage may be required in parallel with depleted oil and gas reservoirs or aquifer storage, especially in locations without local geological salt accumulations, to accommodate short-term supply and demand disruptions.

2 STUDY ASSUMPTIONS AND METHODOLOGIES

This section first discusses the assumptions used in the generalized, vertically-integrated, single-source-to-sink study including the most likely required CIS reservoir construction time as well as the most likely required pipeline construction time. Exhibit 2-1 shows a visual representation of basic model inputs, assumptions, and outputs, for estimating the downsized pipeline length between a CO₂ source and end-user (storage) needed to offset the cost of CIS. Next, the section describes the methodologies to evaluate the economics of a CIS reservoir of the most appropriate size for a given anthropogenic source using information and data from NETL's "Underground Natural Gas Storage – Analog Studies to Geologic Storage of CO₂" report (Natural Gas Storage Analog) as a guide. [19] Finally, the section describes the methodology to analyze the pipeline economics of a project using data from open sources and the FECM/NETL CO₂ Transport Cost Model (CO₂_T_COM). [41]

Exhibit 2-1: Basic CIS economic model inputs, assumptions, and outputs

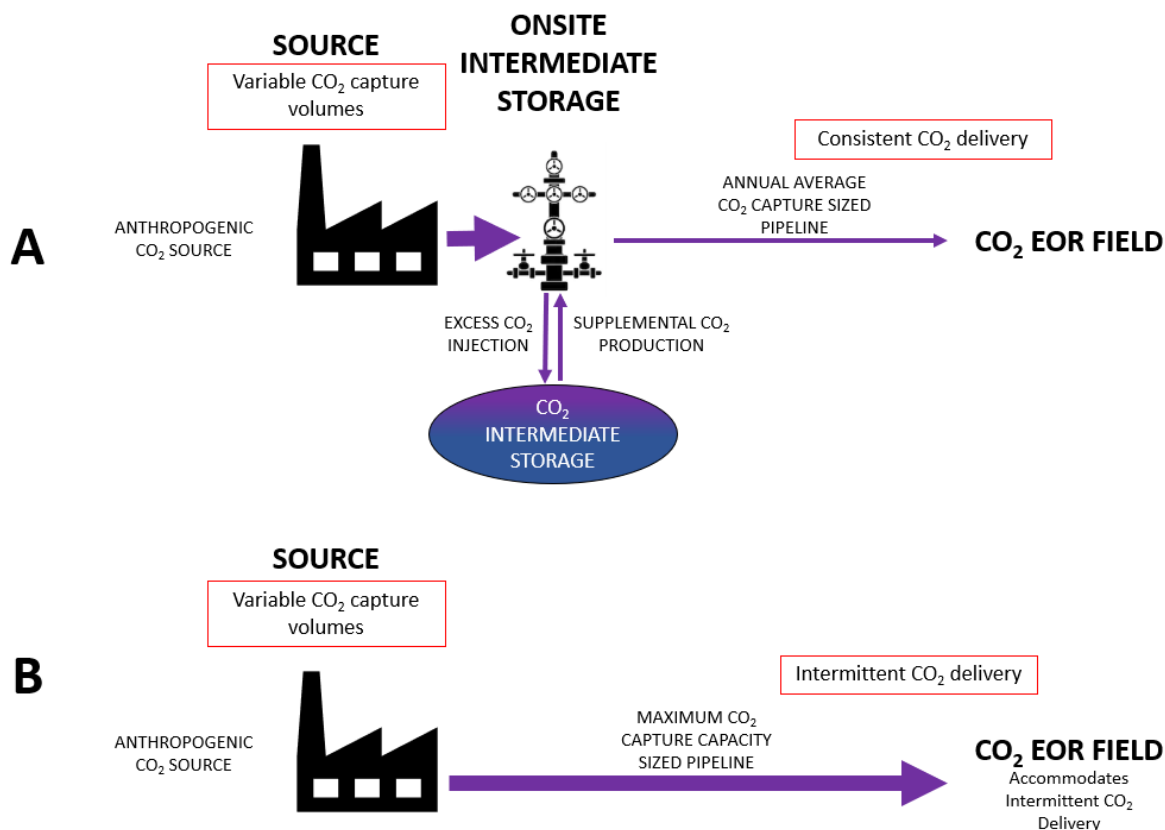


2.1 GENERAL MODEL ASSUMPTIONS

In this study the total cost of the CIS reservoir, as adapted from the Federal Energy Regulatory Commission (FERC) report on underground natural gas storage (UNGS), is compared to the net present value of pipeline construction and operation savings. [20] [41] These savings are realized by constructing a smaller diameter, fully utilized CO₂ pipeline sized to transport a CO₂ source's average capture rates in conjunction with an onsite CIS, (A) in Exhibit 2-2, compared to an under-utilized pipeline capable of transporting source peak capture rates, (B) in Exhibit 2-2.

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Exhibit 2-2: (A) Proposed project cost savings arrangement with CIS compared to (B) larger pipeline sized to maximum capture rates with no CIS



To compare CIS costs with pipeline savings in this study, it is assumed that the CIS reservoir is located onsite, i.e., underlying the same geographic location as the CO₂ source. It is assumed, therefore, that the cost and timing of constructing the pipeline between the CO₂ source and the CIS reservoir is minimal and included in CO₂ capture equipment total cost and timing of construction, which is beyond the scope of this study.

To discern the approximate time required to construct a new CIS reservoir, data was analyzed from a report by Foster Associates using UNGS as an analog. [42] The report provides excellent data regarding the most likely time from government regulatory approval to operation of the CIS, which is approximately 2 years for depleted oil and natural gas fields, aquifers, and salt caverns. [42] The CO₂_T_COM, which is used to calculate the associated pipeline costs for each CIS scenario, assumes a default of 3 years of construction time for its pipeline economic calculations. [43] Since data indicates that the construction time for a CIS reservoir is approximately 2 years while the construction time for a CO₂ pipeline is assumed to be approximately 3 years, economic models for this work will assume the total capital expense of the CIS reservoir is uniformly spent over the first 2 years of the project while the capital for the pipeline to market is spent over the first 3 years of the project in a way consistent with the CO₂_T_COM. [43]

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Following the construction phase of the CIS reservoir, the reservoir must be charged with base and working gas prior to operation. Therefore, it is assumed that the CIS reservoir is filled with base gas and working gas during the third year of the project, after the reservoir is constructed but before the downsized CIS to EOR pipeline is operational. The timeline of each capital and operating expense accounted for in this analysis is shown in Exhibit 2-3.

Exhibit 2-3: Typical timeline of capital and operating costs of the CO₂ pipeline and CIS reservoir in this study

Permitting and Construction		Operations			Closure
CIS Construction	Pipeline Construction	CIS Operation		Pipeline Operation	CIS Closure
Years 1 and 2	Years 1, 2, and 3	Year 3	Years 4 through 33	Years 4 through 34	Year 34
Permitting and construction of CIS reservoir	Permitting and construction of the downsized CO ₂ transport pipeline from CIS to end-user	Injection of CIS base and working gas capacity	Injection and withdrawal of CIS working gas	Pipeline operating expenses	Withdrawal of all CIS working gas, and for steel tanks and salt caverns, all base gas.
CIS CAPEX from FERC's UNGS report [20]	CAPEX from CO ₂ _T_COM	CIS OPEX assumed to be completely offset by downsized pipeline OPEX		OPEX from CO ₂ _T_COM	CIS OPEX assumed to be completely offset by downsized pipeline OPEX

Total CIS costs in Exhibit 2-4 are converted from FERC's UNGS report. [20] The original operational specifications were specific to natural gas storage but were modified here to be relevant to CO₂. The modifications include adjustment for CO₂ density at depth and assume that the underground storage is at approximately 1,372 m (4,500 ft) true vertical depth, where the temperature and pressure should be approximately 13.3 MPa (1,935 Psi) and 50°C (122 °F). [20] [19] Density of CO₂ under these conditions (659 kg/m³) compared to those of natural gas (92.3 kg CH₄/m³) and natural gas at standard temperature and pressure (0.717 kg CH₄/m³) results in a conversion factor of approximately 145,000 tonnes of CO₂ per Bcf of natural gas storage. Steel tank storage costs are estimated as the average of values from literature with density of CO₂ maintained at the triple point, where the density of CO₂ is highest. [44] [45] [46] Salt caverns as listed are shown to go as low as \$69 per tonne of working capacity due to the FERC reporting that salt cavern natural gas storage along the coast of the Gulf of Mexico can reach as low as \$10MM per Bcf of working storage. [20]

Exhibit 2-4: Comparison of total CIS costs and characteristics [20] [29]

Reservoir Type	Facility Expansion (2015\$/tonne Working CO ₂ Capacity)	New Facility (2015\$/tonne Working CO ₂ Capacity)	Injection Period (days)	Withdrawal Period (days)	Base Gas Requirement (%)	Average Working Gas Capacity (Bcf)
Salt caverns	69 - 207	69 - 241	20 to 40	10 to 20	30	5
Depleted oil and gas reservoirs	117	138	200 to 250	110 to 150	50	11

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Aquifers	234	290	201 to 250	111 to 150	80	10
Steel tanks	N/A	1,120	N/A	N/A	0	N/A

An additional assumption about CIS reservoir cost is that the minimum total cost for any of the underground storage options is \$5MM. This is based on an analysis of data from the EIA that shows the smallest operating salt cavern in the United States has a capacity of 0.17 Bcf of natural gas—equivalent to just over \$5MM of expense based on the economic (total CIS cost) assumptions of the model shown in Exhibit 2-4. [29] A low-cost (\$69/tonne) salt cavern with capital expenses of \$5MM is assumed in all cases that call for salt caverns that would be less expensive. Only when the steel tank equivalent capital expense drops below \$5MM, at working storage capacities less than 4,500 tonnes, are steel tanks assumed to be the most economical option.

Finally, differences in the operating and capital expenses of the different pipelines are accounted for in the economic model with calculations from the CO₂_T_COM. [43] [41] Operating expenses are important to include in the analysis of the pipeline cost because even though the capital expense of smaller pipelines go down when decreasing the maximum rate of transport, sometimes the operating expense increases for smaller pipelines. [41] Contributing factors include more electricity for booster pumps to maintain higher pressure in the smaller pipelines to transport the CO₂. Even though smaller pipelines have a higher unit cost per tonne, to realize the unit cost savings of larger pipelines, the larger pipeline must have an equal utilization. Since the scope of this report is limited to analysis of single CO₂ sources, unit cost savings benefits of larger pipelines are not realized due to larger pipelines having lower utilization factors than smaller pipelines used with CIS.

2.2 CIS RESERVOIR SIZING METHODOLOGY

To determine CIS economics for a source-to-sink CO₂ transport system, the required working CO₂ capacity for the associated CIS must be calculated. The minimum required working gas capacity of CO₂ is used to determine CIS reservoir development costs (with data from Exhibit 2-4). To determine the minimum required working CO₂ capacity for the CIS reservoir, Equation 2-1 is used, accounting for the size and capacity factor of the CO₂ source. According to Gao et al., working CIS capacity should be sized to 150% of the loading capacity of a ship in a pipeline and ship system. [39] Therefore, underground CIS is assumed to be sized to 150% of the expected required working storage capacity in this analysis to accommodate unexpected events and give room for fluid expansion and contraction as steady-state conditions of the reservoir are reached—incorporated as the 1.5 multiplier in Equation 2-1. [39]

$$\text{Required Working Capacity (RC)} = \frac{1.5 * CR_{avg} * (100 - CF)}{100 * CY} \quad \text{Equation 2-1}$$

Where

- RC = required working capacity (tonnes)
 CR_{avg} = yearly average capture rate (tonnes) = yearly downstream demand
 CF = capacity factor (%)
 CY = number of cycles per year

2.2.1 Calculating Petra Nova CIS Parameters

The number of cycles per year (CY in Equation 2-1) is an important parameter for determining CIS capacity sizing and economics. CY can be determined if the CO₂ capture rate data over time is available or can be estimated. A case study is presented in using two years of weekly carbon capture data from Unit 8 of the WA Parish electricity generation facility (Petra Nova) attained from ABB Velocity Suite, shown in Exhibit 2-5. [47] The weekly data following the December 29, 2016 start of commercial Petra Nova operation were used to demonstrate how a timeseries of CO₂ capture rates can be used to determine CIS parameters needed for later economic analysis like the break-even downsized pipeline lengths discussed in Section 3. [13]

Petra Nova's maximum designed capture rate is 4,700 tonnes/d, while analysis of the data in Exhibit 2-5, shows a maximum weekly average capture rate of 4,758 tonnes/d, and an average of just under 3,200 tonnes/d was captured. On an annual basis, the maximum capture rate in the data set is equivalent to 1.737 Mtpa, and an average capture rate is equivalent to 1.168 Mtpa, resulting in an effective 67% capacity factor. These rates are further confirmed by the announcement of Petra Nova's milestone of 1 million short tons of CO₂ captured in October 2017. [47]

Assuming Petra Nova's 81-mile CO₂ transport pipeline [48] was originally constructed to maintain a constant 3,200 tonnes/d of flow to the West Ranch oil field by developing an onsite salt cavern CIS (assuming geologically practicable), Exhibit 2-6 shows the need for a minimum of 164,000 tonnes worth of intermediate CO₂ working gas capacity to store excess CO₂ during periods of capture greater than 3,200 tonnes/d, available for withdrawal to fill the CIS to CO₂ EOR pipeline during periods of capture rates less than 3,200 tonnes/d. To allow for 50% extra capacity for fluid expansion and contraction or in case of unforeseen events, a CIS for the Petra Nova project is estimated to require 246,000 tonnes of working gas capacity. [39]

An important feature of Exhibit 2-6 is the smaller scale inventory changes that take place within the larger time scale annual inventory cycle. There would be 17 minor withdrawals over the 2-year time period, and there would be two large-scale withdrawal intervals over the same time frame. Since salt caverns are the only large CIS reservoir type that can be cycled more than once per year, Petra Nova's data promotes the concept that salt caverns are likely to be the first type of CIS reservoir. [19] The effective cycle rate (CY in Equation 2-1), for a CIS for Petra Nova can be

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solved for assuming 246,000 tonnes of working gas capacity (RC), 67% capacity factor (CF), and an average yearly capture rate (CR_{avg}) of 1.168 Mtpa: 2.33 cycles per year.

Exhibit 2-5: Weekly average rate of CO₂ capture from Petra Nova

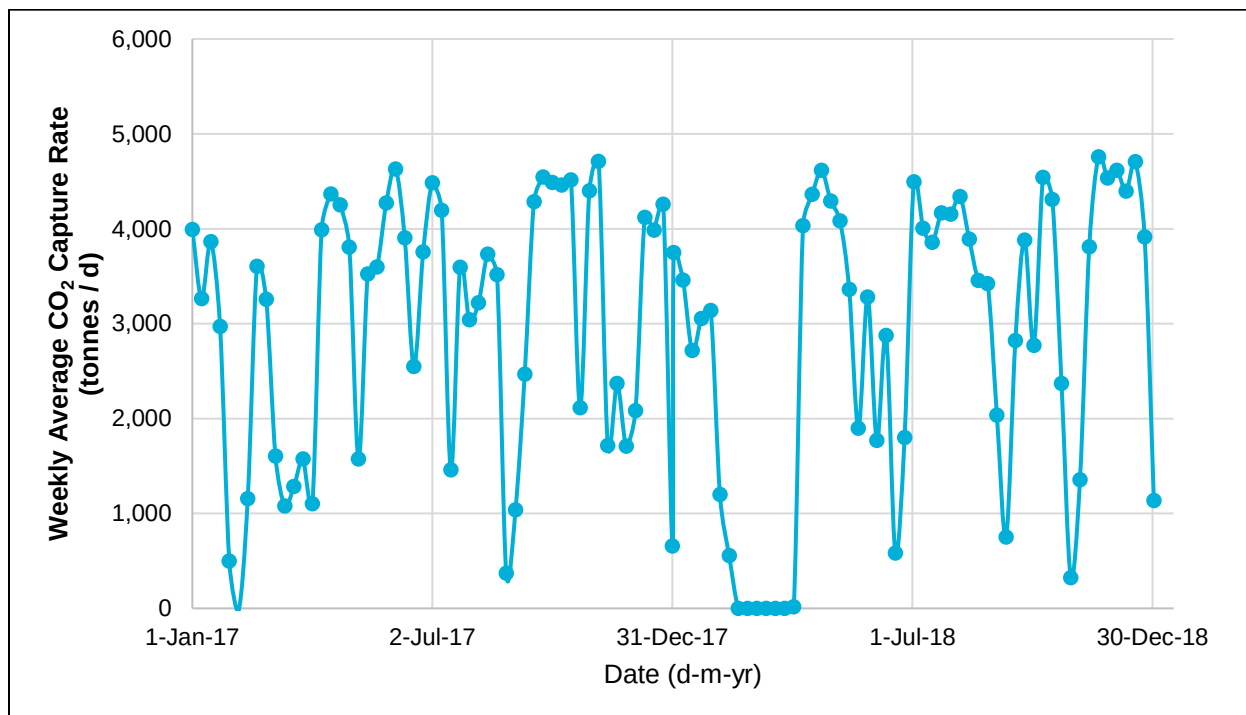
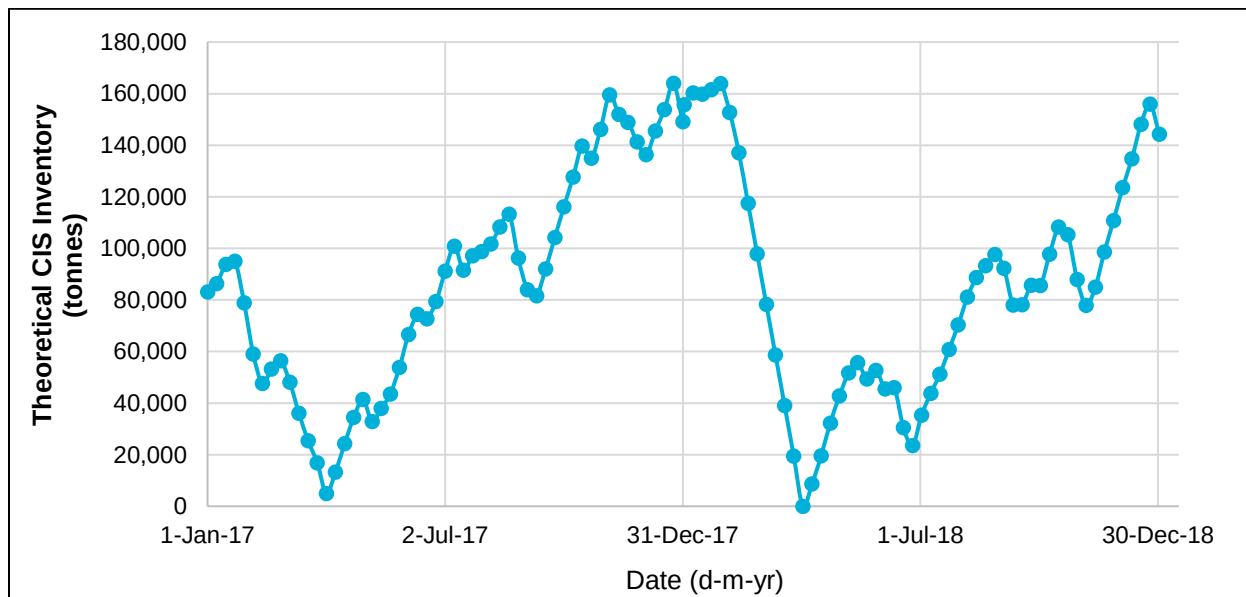


Exhibit 2-6: Inventory of a theoretical CIS reservoir for Petra Nova to allow a constant 3,200 tonnes/d of CO₂ supply



2.3 CIS RESERVOIR SIZING ECONOMICS

Required capacity can be multiplied by the facility expansion cost per tonne of capacity in Exhibit 2-4 to estimate the total cost required to construct the CIS. These costs are assumed to include all capital and operating costs and be spent evenly over the two years of construction time. [20] [19]

Exhibit 2-7, adapted from Vikara et al. (2018), [49] shows the average capacity factors from several anthropogenic CO₂ sources. These values can be applied to Equation 2-1 to calculate several of the values given in Exhibit 2-8, Exhibit 3-1, and Exhibit 3-2. [49] The estimated total CIS working capacity shown in Exhibit 2-8, assuming 1, 2, 3, 6, and 12 cycles per year from the sources. Exhibit 2-9 shows the estimated CAPEX required for the CIS reservoirs based on the different CO₂ sources and potential cycle rates.

Exhibit 2-7: Average capacity factors of select anthropogenic CO₂ sources

	Plant	Reported Net Power or Product Output	Reported Average Capacity Factor (%)	Peak Rate of CO ₂ Captured (Mt/yr)
Bituminous Coal-Powered Plants [50] [51]	Subcritical PC	550 MW _e	54 [17]	3.71
	SCPC	550 MW _e	54 [17]	3.58
	IGCC Shell	497 MW _e	54 [17]	3.09
	IGCC CB&I	513 MW _e	54 [17]	3.21
	IGCC GEE Radiant	543 MW _e	54 [17]	3.19
	IGCC GEE Quench	494 MW _e	54 [17]	3.19
Natural Gas-Powered Plant [50]	NGCC 2013 F-Class CT	559 MW _e	55 [17]	1.50
Industrial Plants [52]	Ethanol	50 M gal/yr	97 [16]	0.14
	Ammonia	907,00 tonnes/yr	80 [53]	0.46
	Ethylene oxide	364,500 tonnes/yr	94 [54]	0.12
	Natural gas processing	500 MMscf/d	68 [18]	0.65
	Coal-to-Liquids	50,000 bbl/d	67 [55]	8.74
	Gas-to-Liquids	50,000 bbl/d	90 [56]	1.86
	Refinery hydrogen	59,000 tonnes/yr	99 [57]	0.27
	Iron/steel	2.54 Mt/yr	88 [58]	3.90
	Cement	992,500 tonnes/yr	82 [59]	1.14

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Exhibit 2-8: CIS working capacity estimates for select CO₂ sources and scenarios

	Plant	Required CIS Working Capacity (Mt)				
		1 Cycle Per Year	2 Cycles Per Year	3 Cycles Per Year	6 Cycles Per Year	12 Cycles Per Year
Bituminous Coal-Powered Plants [50] [51]	Subcritical PC	1.380	0.690	0.460	0.230	0.115
	SCPC	1.332	0.666	0.444	0.222	0.111
	IGCC Shell	1.152	0.576	0.384	0.192	0.096
	IGCC CB&I	1.194	0.597	0.398	0.199	0.099
	IGCC GEE Radiant	1.187	0.593	0.396	0.198	0.099
	IGCC GEE Quench	1.187	0.593	0.396	0.198	0.099
Natural Gas-Powered Plant [50]	NGCC 2013 F-Class CT	0.560	0.280	0.187	0.093	0.047
Industrial Plants [52]	Ethanol	0.006	0.003	0.002	0.001	0.001
	Ammonia	0.111	0.056	0.037	0.019	0.009
	Ethylene oxide	0.010	0.005	0.003	0.002	0.001
	Natural gas processing	0.211	0.106	0.070	0.035	0.018
	Coal-to-Liquids	2.901	1.450	0.967	0.483	0.242
	Gas-to-Liquids	0.251	0.125	0.084	0.042	0.021
	Refinery hydrogen	0.004	0.002	0.001	0.001	0.000
	Iron/steel	0.614	0.307	0.205	0.102	0.051
	Cement	0.251	0.126	0.084	0.042	0.021

Exhibit 2-9: CAPEX costs for select CO₂ sources and scenarios assuming low cost (Gulf Coast) salt cavern (\$69/tonne) CIS

	Plant	CIS Reservoir Cost (2015\$MM)				
		1 Cycle Per Year	2 Cycles Per Year	3 Cycles Per Year	6 Cycles Per Year	12 Cycles Per Year
Bituminous Coal-Powered Plants [50] [51]	Subcritical PC	95.22	47.61	31.74	15.87	7.94
	SCPC	91.89	45.94	30.63	15.31	7.66
	IGCC Shell	79.51	39.75	26.50	13.25	6.63
	IGCC CB&I	82.37	41.18	27.46	13.73	6.86
	IGCC GEE Radiant	81.89	40.94	27.30	13.65	6.82
	IGCC GEE Quench	81.89	40.94	27.30	13.65	6.82

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Natural Gas-Powered Plant [50]	NGCC 2013 F-Class CT	38.66	19.33	12.89	6.44	-
Industrial Plants [52]	Ethanol	-	-	-	-	-
	Ammonia	7.66	-	-	-	-
	Ethylene oxide	-	-	-	-	-
	Natural gas processing	14.57	7.29	-	-	-
	Coal-to-Liquids	200.15	100.07	66.72	33.36	16.68
	Gas-to-Liquids	17.28	8.64	5.76	-	-
	Refinery hydrogen	-	-	-	-	-
	Iron/steel	42.35	21.18	14.12	7.06	-
	Cement	17.33	8.66	5.78	-	-

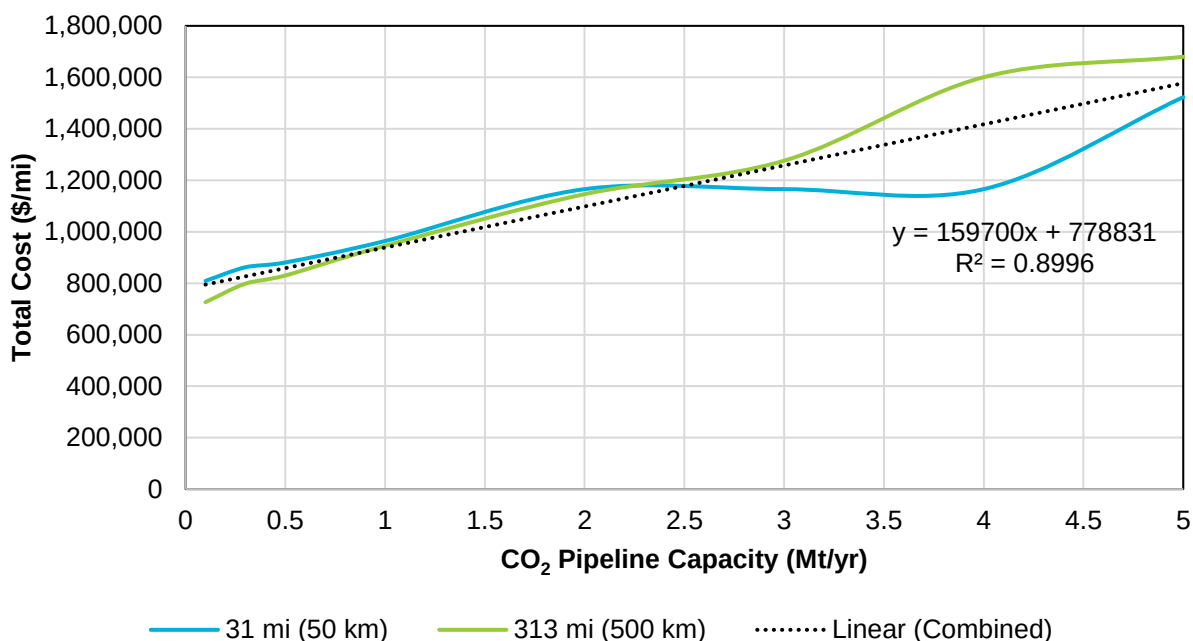
2.4 PIPELINE ECONOMICS

The change in total pipeline costs is calculated by running the CO₂_T_COM for pipelines of varying CO₂ transport capacities and creating a best-fit relationship between net present cost per mile (\$/mi) and CO₂ transport pipeline capacity. This best-fit relationship is used to calculate the difference in capital and operating expenses between a larger capacity under-utilized pipeline designed to transport up the maximum CO₂ capture rate at any time and a smaller fully-utilized pipeline designed to transport the CO₂ at yearly average rates in conjunction with CIS. Some anthropogenic CO₂ sources only capture about 0.12 Mt/yr per Exhibit 2-7, therefore the CO₂_T_COM is run down to a transport rate of 0.1 Mt/yr corresponding to a minimum inner diameter of the pipeline of 2.5 inches (in) (nominal pipe diameter of 4 in). Results of running the transport cost model down to 0.1 Mt/yr is the linear correlation shown in Exhibit 2-10. [41]

Data and analysis of the total pipeline costs per mile resulting from these runs serves as a foundation of the economic analysis presented in this report. The CO₂_T_COM [41] was used to perform runs to determine total 30-year net present value pipeline costs (CAPEX plus OPEX) of pipelines (Exhibit 2-10).

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Exhibit 2-10: Total (CAPEX plus OPEX) net present pipeline cost vs. pipeline capacity



Net present value cost difference of pipelines of varying transport capacities are calculated by first finding the net present cost per mile of a pipeline sized for peak and annual average CO₂ capture rates on the linear fit in Exhibit 2-10. The difference between these values is displayed as the 'Pipeline Net Present Cost Difference (\$/mi)' in Exhibit 2-11 and reflects the cost savings on the pipeline portion of the CCUS network by utilizing a downsized pipeline vs. a larger pipeline built to handle peak capacity. This analysis shows that peak rate of CO₂ capture and the average capacity factor are the two largest factors that determine the net present value transport cost savings per mile of pipeline required.

Exhibit 2-11: Differences in total 30-year pipeline costs from select CO₂ sources assuming yearly average capture rates compared to peak capture rates

	Plant	Reported Average Capacity Factor (%)	Peak Capture Rate Assuming No CIS (Mt/yr)	Average Capture Rate with CIS (Mt/yr)	Pipeline Net Present Cost Difference (\$/mi)
Bituminous Coal-Powered Plants [50] [51]	Subcritical PC	54 [17]	3.71	2.00	273,087
	SCPC	54 [17]	3.58	1.93	263,505
	IGCC Shell	54 [17]	3.09	1.67	226,774
	IGCC CB&I	54 [17]	3.21	1.73	236,356
	IGCC GEE Radiant	54 [17]	3.19	1.72	234,759

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	IGCC GEE Quench	54 [17]	3.19	1.72	234,759
Natural Gas-Powered Plant [50]	NGCC 2013 F-Class CT	55 [17]	1.50	0.83	106,999
Industrial Plants [52]	Ethanol	97 [16]	0.14	0.14	0
	Ammonia	80 [53]	0.46	0.37	14,373
	Ethylene oxide	94 [54]	0.12	0.11	1,597
	Natural gas processing	68 [18]	0.65	0.44	33,537
	Coal-to-Liquids	67 [55]	8.74	5.86	459,936
	Gas-to-Liquids	90 [56]	1.86	1.67	30,343
	Refinery hydrogen	99 [57]	0.27	0.27	0
	Iron/steel	88 [58]	3.90	3.41	78,253
	Cement	82 [59]	1.14	0.93	33,537

The total cost of each CIS reservoir outlined in Exhibit 2-8 is divided by the ‘Pipeline Net Present Cost Difference (\$/mi)’ in Exhibit 2-11 to solve for the most likely pipeline length where CIS with a downsized pipeline becomes cheaper than an under-utilized pipeline sized to peak capture rates. Results of calculating these “break-even” pipeline lengths and other associated concepts are explored in the results section.

3 RESULTS

Feasibility of CIS integration is based on the economic value it generates for the given CCUS scenario. The CIS reservoir generates value when it can decrease the total cost to transport the CO₂ from a given source to an appropriate market such as an EOR reservoir or hub. Both general and detailed economic analyses are performed to determine the economic value of CIS. The general economic analysis is meant to provide guidance for future projects and quantify a pipeline length that provides an economic advantage from CIS. Under these conditions, it is less expensive for a project to create onsite CIS and downsize the pipeline rather than construct a larger pipeline between source and storage to accommodate the maximum rates of CO₂ capture that would be under-utilized most of the time. The general economic analyses can serve as preliminary guidance on the value of salt cavern CIS in the most likely “first mover” location, along the coast of the Gulf of Mexico.

3.1 GENERAL ECONOMIC ANALYSIS – CIS TO AVOID OVER-SIZED PIPELINES

The difference of the CIS reservoir cost from Exhibit 2-11 is divided by the length-averaged pipeline cost differences from to solve for the length of down-sized pipeline required to pay for the addition of CIS reservoir with CAPEX greater than \$5MM (shown in Exhibit 3-1). These calculations show that as the CO₂ source downtime is spread over larger numbers of equal-sized annual cycles, decreasing the required CIS capacity, the length of pipeline required to offset the cost of the CIS reservoir decreases. [19] [41] Exhibit 3-1 displays the approximate break-even pipeline length needed to pay for CIS assuming theoretical low-cost salt cavern storage along the coast of the Gulf of Mexico that the FERC estimates to equal \$10MM per Bcf of natural gas storage, equal to \$69/tonne CO₂ assuming an approximate conversion factor of 145,000 tonnes of CO₂ per Bcf of equivalent natural gas storage. [20] [19] Exhibit 3-1 suggests that with increases in the number of CIS cycles per year, the CO₂ source with onsite CIS can be located closer to the storage site and remain economical.

Exhibit 3-1: Break-even pipeline lengths with total cost difference equal to the CAPEX of low cost (Gulf Coast) salt cavern (\$69/tonne) CIS

	Plant	Break-even Pipeline Length (mi)				
		1 Cycle Per Year	2 Cycles Per Year	3 Cycles Per Year	6 Cycles Per Year	12 Cycles Per Year
Bituminous Coal-Powered Plants [50] [51]	Subcritical PC	349	174	116	58	29
	SCPC	349	174	116	58	29
	IGCC Shell	351	175	117	58	29
	IGCC CB&I	348	174	116	58	29
	IGCC GEE Radiant	349	174	116	58	29

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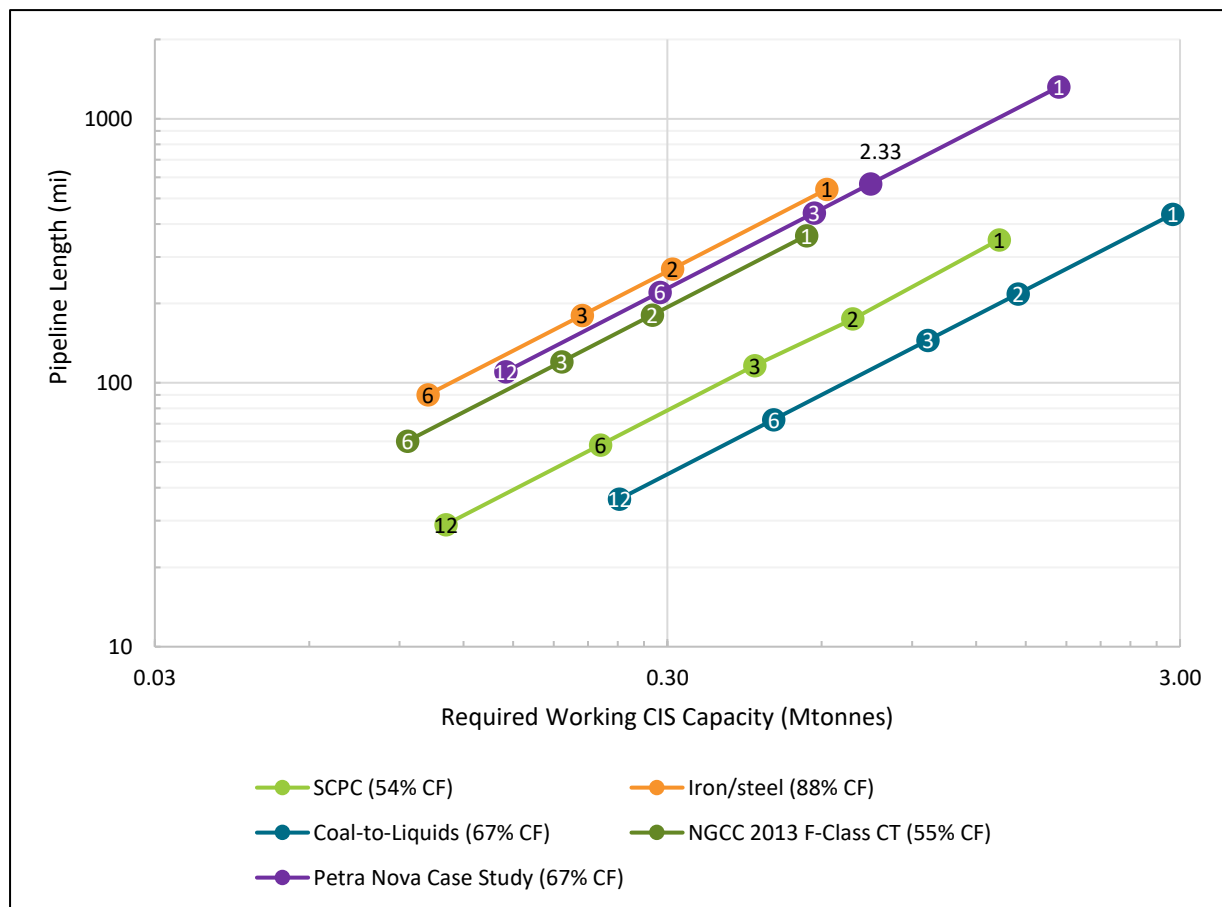
	IGCC GEE Quench	349	174	116	58	29
Natural Gas-Powered Plant [50]	NGCC 2013 F-Class CT	361	181	120	60	-
Industrial Plants [52]	Ethanol	-	-	-	-	-
	Ammonia	533	-	-	-	-
	Ethylene oxide	-	-	-	-	-
	Natural gas processing	435	217	-	-	-
	Coal-to-Liquids	435	218	145	73	36
	Gas-to-Liquids	570	285	190	-	-
	Refinery hydrogen	-	-	-	-	-
	Iron/steel	541	271	180	90	-
	Cement	517	258	172	-	-

A visual representation of selected data from Exhibit 3-1, and from the Petra Nova data presented in Section 2.2.1, is shown in Exhibit 3-2. These exhibits display the general break-even pipeline lengths at which it is cheaper to install a smaller diameter pipeline with CIS to allow for nearly 100% pipeline utilization compared to a larger pipeline sized for the peak transport rates with no CIS. Increasing the number of annual cycles (number labels shown on the data points) at a given capacity factor and average capture rate decreases the break-even pipeline length due to lower CIS capacity for multiple smaller cycles compared to one larger cycle.

The FERC's UNGS report indicated that salt caverns along the coast of the Gulf of Mexico can have significantly reduced required CAPEX to construct (equivalent to \$69/tonne of CO₂ storage compared to \$207/tonne for U.S. average salt caverns and \$117/tonne for depleted oil and gas reservoirs). [20] Assuming this reduction in required CAPEX for the CIS reservoir (Exhibit 3-2) shows the drastically reduced break-even pipeline lengths to pay for CIS for representative CO₂ sources.

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Exhibit 3-2: Break-even pipeline length to pay for (low cost) Gulf Coast salt cavern CIS vs. required CIS capacity for select CO₂ source types and CIS cycles per year



Analysis captured in Exhibit 3-2 assumes the anthropogenic sources have industry average capacity factors (in parentheses in Exhibit 3-2) while the required storage to accommodate those capacity factors are varied. Storage capacity is varied by the cycle rate (the data labels in each data point in Exhibit 3-2) associated with downtime at the CO₂ source, because if there are two downtime “cycles” per year rather than one, the required working storage capacity per year would be half that of one cycle per year, assuming the same source capacity factor and average annual CO₂ generation.

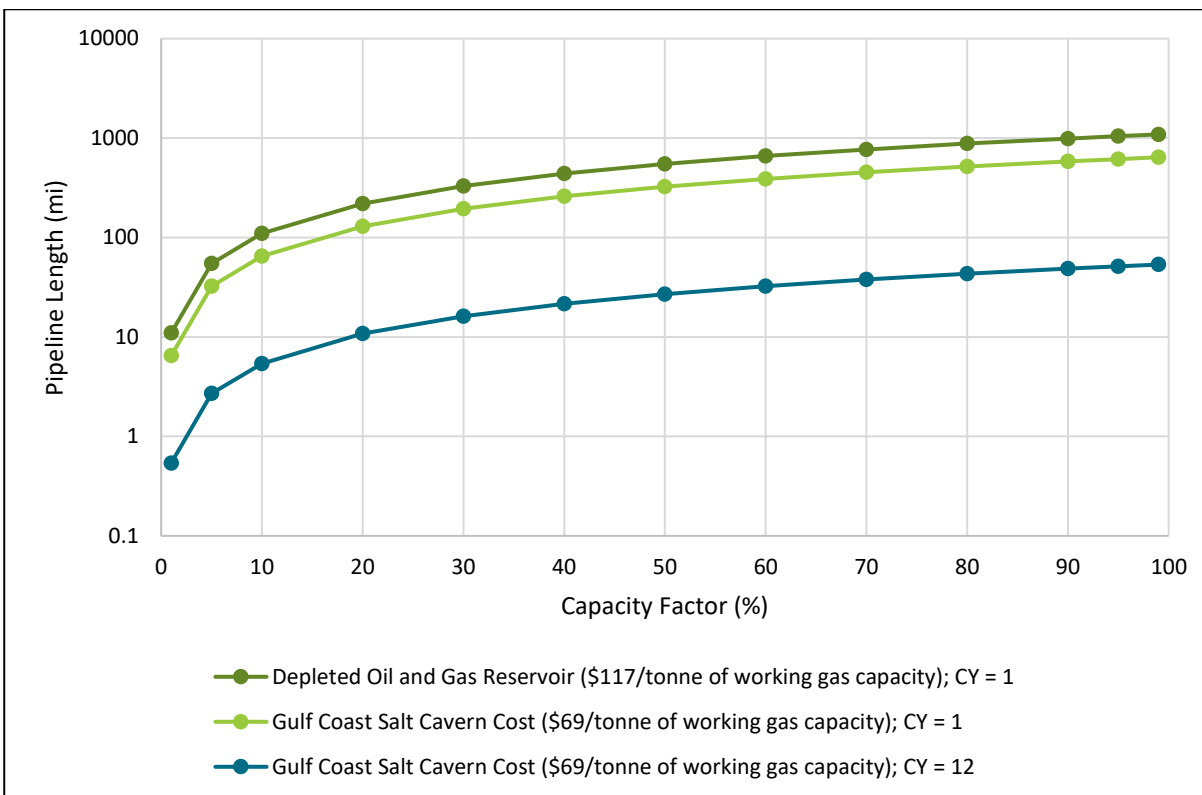
Petra Nova’s break-even pipeline length (the purple data point in Exhibit 3-2), from the CIS working capacity and the calculated cycle rate derived from the first two years of actual CO₂ capture data in Section 2.2.1, demonstrates that the break-even pipeline length for CIS would need to exceed 567 miles, much further than the 81-mile pipeline used for the project. [48] However, if 12 cycles per year were required, the break-even pipeline length for CIS would be closer to 100 miles, similar to the 81-mile pipeline used for the project.

General relationships between the capacity factor of an anthropogenic source and the break-even pipeline length are derived for both “low cost” salt caverns near the Gulf Coast and depleted oil and gas reservoirs (the next lowest cost CIS reservoir type). These assume only one

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cycle per year for the required CIS and are shown in Exhibit 3-3. Break-even distances can be adjusted for more than one cycle per year by dividing the break-even distance by the number of cycles per year, as shown by the 12 cycles per year “low cost” salt cavern data.

Exhibit 3-3: Pipeline length where net present cost difference between peak and average rate pipeline pays for 1 or 12 annual cycles with 150% minimum required CIS capacity



4 CONCLUSIONS

This study evaluated the economic value that CIS can add to a single source-to-sink pipeline scenario. General economic modeling analysis shows that at typical anthropogenic CO₂ source capacity factors of near 60%, the only CIS storage option that appears economically viable is a salt caverns with 3 or more cycles per year along the coast of the Gulf of Mexico. Break-even pipeline lengths for the downsized pipelines with multiple cycles to pay for salt cavern CIS reservoir along the coast of the Gulf of Mexico are around 200 miles. Existing CCUS infrastructure projects, like the 81-mile pipeline from the Petra Nova capture facility to the West Ranch CO₂ EOR field, are unlikely to benefit from CIS, based on the first two years of Petra Nova's CO₂ capture data. However, there may be low capacity factor CO₂ sources with large CO₂ capture rates that could benefit from CIS, especially if the cycle rate per year needed is considerably high. CIS may provide additional value if undisrupted CO₂ supply has additional value to the CO₂ end-user, however this concept is not formally explored in this study. This finding is an important consideration for future CCUS endeavors when considering source and sink matching, as well as sustained CO₂ supply.

Two key findings from this analysis are that 1) CIS can have a positive economic value when used in conjunction with a down-sized pipeline to maximize the utilization of the pipeline and 2) CO₂ sources with low CO₂ source capacity factor which would need CIS capable of higher cycle rates per year are the likeliest to benefit economically from CIS deployment. High cycle rate reservoirs necessitate low-cost salt caverns, like those near the coast of the Gulf of Mexico.

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