NETL'S ANALOG STUDIES TO GEOLOGIC STORAGE OF CO_2 – OVERVIEW

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Carbon capture and storage (CCS) is one of many promising strategies for managing and reducing the anthropogenic (i.e., man-made) emissions of CO_2 into the atmosphere. CCS involves separating and capturing CO_2 from fossil fuel-based power generation and industrial sources, transporting it to a geologic storage site or enhanced oil recovery (EOR) project for storage, and injecting (or beneficially reusing or utilizing it) into a suitable geologic storage or EOR reservoir. CO_2 capture integrated with transport and geologic storage comprises a suite of technologies that can benefit an array of industries including power (fossil, biofuel, and geothermal) and refining. This suite of technologies enables industries to continue operations while emitting less CO_2, providing a powerful tool for managing anthropogenically-derived CO_2.

Several small- and large-scale CCS projects have deployed throughout the world and have demonstrated that significant CO_2 emissions reductions are possible. However, the technology is still considered to be emerging in many regards[1] and widespread CCS deployment faces several challenges, including achieving better cost effectiveness, ensuring overall technical viability of capturing and storing CO_2 at large scales, and securing effective financing agreements.[2,3] In the United States specifically, widespread deployment of CCS may rely on a combination of stable economic incentives and continued research and development advancements to make the technology economically-viable.[4]

CCS research benefits from drawing insights and lessons learned from the history of other commercially prominent energy technologies and analogous industries that were once considered risky and expensive early in their commercial development. The types of analogous

[1] European Zero Emission Technology and Innovation Platform (ZEP). "Future CCS Technologies," 2017.

[2] Global CCS Institute, "The Global Status of CCS: 2017," Australia, 2017.

[3] International Energy Agency (IEA), Carbon Capture and Storage Unit, "Carbon Capture and Storage: Opportunities and Challenges," IEA, Abu Dhabi, United Arab Emirates, 2011.

[4] Eames, F. and Lowman, D., "Section 45Q Tax Credit Enhancements Could Boost CCS," Lexology, 22 February 2018. [Online]. Available: https://www.lexology.com/library/detail.aspx?g=c4595638-43ec-4e7c-8792-aad60aa2fe48. [Accessed 23 July 2018].

industries that have overcome hurdles similar to those currently challenging the development of CCS technology can provide awareness and lessons learned for CCS stakeholders to utilize moving forward.[5]

Examples of industrial (engineered) analogs to CO_2 geologic storage include 1) underground natural gas storage, which has been commercially-operational for over 100 years in the United States (U.S.); 2) deep well waste disposal (injection and disposal of non-hazardous and hazardous wastes into deep confined rock formations), which has occurred in the United States since the 1930s; and 3) CO_2 EOR, which has been commercially-operational since the early 1970s. Given the inherent synergies with CO_2 storage, the U.S. Department of Energy's National Energy Technology Laboratory (NETL) evaluated these three analog industries in the form of three separate, comprehensive studies. Each study provides an overview of the operations, commercial history, prominent regulations, site screening and development considerations, incidents of leakage events (and how they were remediated), and insight on public perception for both the specific analog and CO_2 geologic storage operations in saline-bearing formations—individually and in relation to each other. Findings from comparing synergistic features (e.g., governing regulations, geologic formations used, injection methods, national storage capacity estimates, and leakage mitigation strategies) between industrial analogs and CO_2 storage can not only help address technical and policy-related questions concerning CO_2 geologic storage but also demonstrate that storing CO_2 in subsurface geologic formations at commercial scales can be feasible and carried out effectively and safely if comparable best practices are implemented. The three studies are publicly available on NETL's website, as shown in Exhibit 1.

Exhibit 1. Links to each of the three analog studies on NETL's website

Analog Study	NETL Website Link
Underground Natural Gas Storage – Analog Studies to Geologic Storage of CO_2	https://netl.doe.gov/energy-analysis/details?id=2867
UIC Class I Injection Wells – Analog Studies to Geologic Storage of CO_2	https://www.netl.doe.gov/energy-analysis/details?id=2892
CO_2 Leakage During EOR Operations – Analog Studies to Geologic Storage of CO_2	https://www.netl.doe.gov/energy-analysis/details?id=2893

The objectives of these analog studies are multifold. For instance, each study

- Provides a body of knowledge that specifically relates to the analog's historical and current operations, which may be directly or indirectly relevant to CO_2 geologic storage operations in saline-bearing formations
- Documents site screening and selection methods, site characterization, and operating procedures that may also be relevant to future CO_2 storage operations and highlights instances of how analogs to CO_2 storage overcome shared technical grand challenges

[5] Rai, V., Victor, D., and Thurber, M., "Carbon capture and storage at scale: Lessons from the growth of analogous energy technologies," *Energy Policy*, vol. 38, no. 8, pp. 4089-4098, 2010.

- Documents and enables learning from any reported leakage identified from the analog's operations and remedial actions that worked (as well as those that may not have been successful) in response to leakage events
- Provides documentation of instances of public interaction and perception concerning the development or operation of analog sites to provide insights into issues that might potentially arise during the development of a U.S. Environmental Protection Agency (EPA) Underground Injection Control (UIC) Class VI CO_2 storage well

The three analogs studied were chosen because of their commonalties with CO_2 geologic storage. Most notably, the success of each practice involves the safe injection (and in certain instances, production) of fluids into the subsurface, which is dependent on overcoming common operational and technical challenges in achieving sufficient injectivity, volumetric capacity, and long-term containment (and deliverability for underground natural gas storage). However, despite the commonalities, each analog industry has unique characteristics that make it distinctive from CO_2 geologic storage operations. Understanding the unique perspectives of each analog industry provides important learning opportunities for CCS stakeholders to benefit from moving forward. Aspects of each analog industry are briefly discussed in the following paragraphs, particularly its specific role in the energy market and unique features common to its specific industry. In certain regards, these unique aspects are a few examples that make each analog different from geologic storage of CO_2.

Underground natural gas storage in subsurface reservoirs has proven to be a critical component of the natural gas supply system in the United States and is necessary for meeting seasonal demand requirements as well as insuring against unforeseen supply disruptions. It involves injecting natural gas into subsurface storage reservoirs such as saline-bearing aquifers (similar to those commonly used in CO_2 storage operations), depleted oil and gas reservoirs, or salt caverns. Injection occurs during periods of low demand and withdrawal during periods of peak demand.[6] This whole process begins with natural gas being produced from a subsurface hydrocarbon reservoir, transported via a pipeline network, and then injected back into a subsurface storage reservoir as part of the overall natural gas supply network. Underground natural gas storage reservoirs are often assessed on their ability to store natural gas (i.e., volumetric capacity) and the rate by which the natural gas can be injected into the subsurface (i.e., injectivity) and produced (i.e., deliverability). Each reservoir type has unique injectivity and deliverability characteristics. Additionally, the spatial distribution of each reservoir type is highly varied across the United States. Not all gas injected and stored is ultimately reproduced as part of underground storage operations. A base gas volume (also referred to as a cushion gas) of natural gas is retained in the reservoir at a relatively constant volume to maintain adequate pressure and deliverability rates throughout periods of withdrawal. The volume of base gas needed to maintain pressure varies by reservoir type. The maximum amount of natural gas that can be stored and is available to the market is called the working gas volume. It is the difference between the total gas storage capacity and base gas volume for a given storage facility. The

[6] Federal Energy Regulatory Commission, "Current State of and Issues Concerning Underground Natural Gas Storage," 30 September 2004. [Online]. Available: https://www.ferc.gov/EventCalendar/Files/20041020081349-final-gs-report.pdf. [Accessed 16 May 2018].

cycle of increasing then decreasing reservoir pressure over time as part of the injection and withdrawal process provides an interesting contrast to the “one-way” injection and storage of CO_2 concept, where reservoir pressure is likely to steadily increase over time during the injection process. Subsurface storage sites for both natural gas storage and CO_2 storage must meet certain regulatory standards pertaining to the design, construction, operations, maintenance, demonstration of well integrity, monitoring, threat/hazard identification and risk assessment, and emergency response and preparedness to ensure safe and effective operations. Both practices face a similar set of technical challenges as part of implementation and may use similar equipment and infrastructure as part of deployment. However, the two practices differ significantly in the governing bodies responsible for overseeing operations. The governing body overseeing natural gas storage relies heavily on whether the storage field in question serves inter or intrastate commerce. If a storage field serves interstate commerce, it is subject to the jurisdiction of the Federal Energy Regulatory Commission; otherwise, it is state-regulated.[7] As for CO_2 storage operations, the U.S. EPA’s UIC Program oversees and regulates this operation through their Class VI injection well regulations.

Deep well injection of wastes (both non-hazardous and hazardous) provides an economically viable way to dispose of this material underground with little or no pretreatment.[8] This practice involves the injection of liquid waste material into isolated geologic strata through a well, which, in turn, permanently isolates the disposed fluids from the biosphere. Deep well waste injection has been, and continues to be, a low-risk method of liquid waste management that has proved to be safe and effective.[9] Non-hazardous and hazardous waste disposal via deep well injection is similar to CO_2 storage in terms of practice, well design, and governing regulations. Both practices are regulated by the U.S. EPA’s UIC Program, but under different well classes – Class I for deep well waste disposal and Class VI for CO_2 storage. There is a long history of subsurface liquid waste disposal practices using wells in the United States. This history provides insight into lessons learned associated with the evolution of operations, emergence and progression of governing regulations related to subsurface injection, and best practices for overcoming critical technical challenges. The creation of UIC regulations in 1980 established technical requirements for siting, construction, operation, and closure of injection wells to ensure safe operations and protect underground sources of drinking water (USDW). Findings and lessons learned from reviewing the operational history of deep well waste disposal in the United States were incorporated as part of the development of the initial UIC regulatory requirements. In fact, prior to the establishment of the UIC regulations in 1980, there had been several leakage events noted as part of deep well waste disposal practices due to inappropriate injection procedures and well designs. Since establishment of the UIC regulations in 1980, only four significant cases of injectate migration occurred due to hazardous well operations. Through mitigation of these

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[7] U.S. Energy Information Administration (EIA). “The Basics of Underground Natural Gas Storage.” 16 November 2015. [Online]. Available: https://www.eia.gov/naturalgas/storage/basics/. [Accessed January 2017).

[8] Encyclopaedia Britannica, "Hazardous-waste management: Treatment, Storage, and Disposal," [Online]. Available: https://www.britannica.com/technology/hazardous-waste-management/Treatment-storage-and-disposal#ref593347. [Accessed 6 June 2018].

[9] Clark, J., Bonura, D., and Van Voorhees, R., "An overview of injection well history in the United States of America," *Developments in Water Science*, vol. 52, pp. 3-12, 2005.

cases, it is was established that none of them affected drinking water sources.[10] This minimal number of leakages is believed to be attributed to the stringent siting, construction, operation, and testing requirements for Class I non-hazardous and hazardous wells. EPA indicated in the 2001 *Study of the Risks Associated with Class I Underground Injection Wells*[10] that the few instances of contamination associated with subsurface waste disposal via deep well injection prior to 1980 would not have occurred had the 1980 regulations been in place. The existing regulations in the United States relevant to both deep well waste disposal (Class I wells) and geologic storage of CO_2 (Class VI wells) involve protecting USDWs from both brine encroachment and waste/CO_2 plume infiltration. But, overall, UIC Class VI wells are typically bound to more rigorous requirements regarding well construction and site monitoring compared to Class I wells.[11] The differences in requirements are to account for the unique considerations associated with Class VI CO_2 storage, including the long operational timeframes and greater volumes of CO_2 stored in the subsurface compared to UIC Class I wells used for waste disposal purposes. Additionally, supercritical CO_2 is highly buoyant compared to displaced formational fluids and has a greater potential to migrate vertically in the subsurface and endanger shallower formations (including drinking water sources) than that of denser waste types common to Class I deep well disposal practices.[12]

CO_2 EOR has become a vital component of U.S. oil production since its initial commercial application in the 1970s. CO_2 EOR operations involve the injection of CO_2 into depleted oil and gas reservoirs with the intent of maximizing oil and gas production. It is typically implemented as a tertiary recovery process, following primary and secondary (waterflood) production techniques in oil reservoirs. An additional benefit is that CO_2 EOR inherently stores CO_2 as part of its overall process. Both naturally-occurring CO_2 sources as well as CO_2 from anthropogenic sources are used in CO_2 EOR operations. CO_2 captured from anthropogenic sources provides a means to enable the expansion of future EOR development, especially in reservoirs that are good candidates for CO_2 EOR but located far from natural CO_2 resources and the current pipeline network. Because CO_2 EOR offers the value of maximizing oil recovery while also providing a bridge to reducing CO_2 emissions from anthropogenic sources at the same time, it can provide a near-term, cost-effective method for storing CO_2. Like deep well waste disposal and CO_2 storage, CO_2 EOR is regulated by the U.S. EPA's UIC Program but under their Class II injection well regulations. However, the implementation of operations and overall objectives of each are drastically different. For example, the objective of CO_2 storage is to maximize storage of CO_2 from anthropogenic sources, while for EOR, the objective is to maximize oil production through efficient use of CO_2. CO_2 EOR operations typically involve multi-well injection and production configurations that are intended to maximize the efficient sweep of the reservoir. Additionally, CO_2 EOR floods may also include a water flooding as a component of the injection

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[10] U.S. Environmental Protection Agency (EPA), "Class I Underground Injection Control Program: Study of the Risks Associated with Class I Underground Injection Wells," U.S. EPA, Office of Ground Water and Drinking Water, Underground Injection Control Branch, EPA 816-R-01-007, Washington, D.C., 2001.

[11] U.S. Environmental Protection Agency (EPA), "Requirements for all Class I wells and Class I hazardous waste wells," October 2015. [Online]. Available: https://www.epa.gov/sites/production/files/2015-10/documents/page_uic-class1_summary_class1_reqs_508c.pdf. [Accessed 7 February 2017].

[12] Wilson, E. and Keith, D., "Geologic Carbon Storage: Understanding the Rules of the Underground," in 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan, 2002.

strategy to improve sweep efficiency. Similar to underground natural gas storage, CO_2 EOR is a cyclical operation in that some of the injected CO_2 is produced along with the oil; it does not involve a "one-way" injection process like deep well waste disposal or CO_2 storage. However, injection and production operations in CO_2 EOR are concurrent, not sequential as in underground natural gas storage. As a result, CO_2 EOR fields must include the necessary liquids handling and CO_2 recycle and processing facilities at the surface as part of operations. With more than 40 years of CO_2 EOR production, significant CO_2 leakage events have rarely been reported which has made many consider the practice to have had relatively safe operations throughout its history.[13] The demonstration of safe injection of CO_2 via EOR into the subsurface over an extensive operational history provides a substantial foundation for CO_2 storage best practices.

Each industry analog has its own unique purpose and objective, commercial application and experience, governing regulations, and type and physical state of injected fluid, etc., which is discussed in detail within the standalone, analog studies. These studies also discuss the shared commonalties between the industries and CO_2 storage including those in terms of site selection and characterization, operational procedures, and equipment used.[14] Exhibit S-1 in the Supplementary Information provides a brief comparison of some of the key items pertaining to the analog industries and CO_2 storage. It also provides a concise way to review the dissimilar items associated with each industry type.

Through these analog studies, it is evident how underground natural gas storage, deep well waste disposal, and CO_2 EOR provide case studies that enable identification of key features and considerations that are likely to be effective for CO_2 storage, as well as learning points from the extensive operational history of each analog. Throughout the analog studies, readers can expect to find information pertaining to the following items:

- Overview of each analog's history, highlighting important milestones that may have strongly influenced operational best-practices, technology advancements, or regulatory actions that now affect how each analog is implemented today
- Evaluation of the relative prominence of each analog in the United States today
- Discussion of the typical costs associated with implementing each analog, as well as CO_2 storage
- Detailed overview of pertinent regulations and agencies involved in overseeing the analog industry and CO_2 injection operations (Class II and Class VI) in the United States
- Thorough discussion of important considerations pertinent to screening, permitting, operating, and closing candidate sites for both analog industries and CO_2 storage. Engineering equations are utilized, where relevant, to provide a basis for understanding

[13] Hill, B., Hovorka, S., and Melzer, S., "Geologic carbon storage through enhanced oil recovery," *Energy Procedia*, vol. 37, pp. 6808-6830, 2013.

[14] International Energy Agency Greenhouse Gas R&D Programme (IEA GHG), "CCS Site Characterisation Criteria," IEA GHG, 2009/10, 2009.

the parametric importance/contribution of significant geologic and operational parameters needed as part of selecting, characterizing, and operating viable sites

- Review of leakage events from the history of each analog. These events have been analyzed and reviewed to understand the causes of the incidents, as well as the method used to mitigate the leak, so that CO_2 storage site operators can implement best-practices into future operations
- Side-by-side comparisons of major synergistic features (such as governing regulations, geologic formations used, injection methods, national storage capacity estimates, and leakage mitigation strategies) between the analog and CO_2 storage in saline-bearing formations

Supplementary Information

Exhibit S-1 provides a side-by-side comparison of key items (e.g., technology inception and commercial status) between the analog industries (underground natural gas storage, deep well waste disposal, and CO_2 EOR) and geologic storage of CO_2.

Exhibit S-1. Comparison of key items pertaining to analog industries and geologic storage of CO_2

Item	Underground Natural Gas Storage	Deep Well Waste Disposal	CO_2 EOR	CO_2 Geologic Storage
Purpose	Store gas for peak usage months in deep geologic formations (cyclically injected into, as well as withdrawn from)	Disposal of non-hazardous and Resource Conservation and Recovery Act (RCRA)-defined hazardous wastes into deep, confined rock formations below USDWs	Increase hydrocarbon recovery (tertiary recovery) with the use of natural or anthropogenic CO_2 Reduce carbon emissions to atmosphere from anthropogenic CO_2 sources	Reduce CO_2 emissions into the atmosphere through injection of captured CO_2 into deep, confined rock formations for long-term storage (CO_2 typically not reproduced)
Technology Inception	Early 1900s	Subsurface fluid disposal via well: 1930s U.S. EPA UIC regulations promulgated: 1980 Amended UIC Class I regulations to address RCRA specific to hazardous waste: 1988	Early 1970s U.S. EPA UIC regulations promulgated: 1980	Mid-1990s U.S. EPA UIC Class VI well regulations promulgated: 2010
Commercial Status	Well-established commercial industry with 415 active projects in the United States[15]	Well-established commercial industry with over 800 wells active in the United States[16]	Well-established commercial industry with over 100 active projects in the United States[17]	Relatively new concept undergoing pilot-and commercial-scale testing with two wells active in the United States[16]
Formation Types Utilized	Saline-bearing formations Depleted oil and gas reservoirs Salt domes	Saline-bearing formations	Depleted oil and gas reservoirs Residual oil zones Unmineable coal seams Organic shale	Saline-bearing formations
Injected Fluid Phase	Gas	Liquid waste (various types)	Gas Supercritical CO_2	Supercritical CO_2

[15] Interagency Task Force on Natural Gas Storage Safety, "Ensuring Safe and Reliable Underground Natural Gas Storage; Final Report of the Interagency Task Force on Natural Gas Storage Safety," U.S. Department of Energy, Washington, D.C., 2016.

[16] U.S. Environmental Protection Agency (EPA), "Underground Injection Control (UIC) – UIC Injection Well Inventory – State Federal Fiscal Year 2017 UIC Inventory Information," May 2018. [Online]. Available: https://www.epa.gov/uic/uic-injection-well-inventory. [Accessed 4 December 2018].

[17] Oil & Gas Journal, "Table C - Producing CO_2, Other Gas, and Chemical EOR in US," *Oil & Gas Journal*, 2014.

Item	Underground Natural Gas Storage	Deep Well Waste Disposal	CO_2 EOR	CO_2 Geologic Storage
Regulatory Body in the United States	Pipeline Hazardous Materials Safety Administration Federal Energy Regulatory Commission State public utility commissions and state oil and gas boards	U.S. EPA	U.S. EPA	U.S. EPA
Prominent Regulations	Protecting Our Infrastructure of Pipelines and Enhancing Safety Act of 2016 Energy Policy Act of 2005	**Non-hazardous:** Safe Drinking Water Act of 1974 (SDWA) UIC Class I: 40 Code of Federal Regulations (CFR) 144 Subpart A 40 CFR 146 Subpart B 40 CFR 146 Subpart C **Hazardous:** SDWA UIC Class I: 40 CFR 144 Subpart A 40 CFR 146 Subpart C 40 CFR 144 Subpart F 40 CFR 146 Subpart G 40 CFR 148 RCRA Hazardous and Solid Waste Amendments	SDWA UIC Class II: 40 CFR 144 Subpart A 40 CFR 146 Subpart C Clean Air Act Subpart UU	SDWA UIC Class VI: 40 CFR 144 Subpart A 40 CFR 146 Subpart H Clean Air Act Subpart RR
Transport	Pipeline to and from storage site(s)	Truck and rail to centralized storage sites; pipelines used for onsite disposal	Pipelines to project sites and within sites	Pipelines expected from CO_2 source to storage sites
Perspective on the Number of Injection Wells Used	Likely to vary from site to site; the key driver in the number of wells needed is to attain desired peak deliverability Lateral migration of natural gas not considered acceptable; therefore, projects may require many wells	Typically, one or more wells per waste-generating facility Dedicated disposal facilities that serve as centralized commercial injectors, accepting waste for disposal from several different sources, typically have several injection wells	Considerable number of wells (often pattern based [5-spot, 9-spot, etc.]) to maximize CO_2 sweep efficiency and hydrocarbon production	Injection well count tied to mass of captured CO_2 requiring storage injection Spare injection capacity needed to allow well shut-in for maintenance
Prominent Containment Mechanism	Stratigraphic or structural trapping mechanism	Structural trapping via shallower, low permeability formation	Capillary trapping within reservoir	Structural trapping, stratigraphic trapping
Leakage Risks	Wellbore failures Caprock integrity – faults and fractures	Wellbore failures Improperly plugged or completed wells	Wellbore failures Surface equipment leakage	Wellbore failures Caprock integrity – faults and fractures