Lessons Learned from Existing Carbon Capture and Storage Sites

Sam Dunlap

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Mentors: Professors Mentzer & Tackett

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Introduction

Carbon capture and storage (CCS) is a critical technology for mitigating the effects of climate change by reducing CO_2 emissions in the atmosphere. It involves capturing carbon dioxide from industrial sources or directly from the air and securely storing it in geological formations underground. This paper focuses only on the injection side of the process and not the capturing of the CO_2. CCS is a relatively new technology that is constantly changing and innovating new technology. The success and safety of CCS depends on several key aspects, including site selection, measurement, monitoring, verification (MMV) technologies, environmental impact management, and adherence to regulatory frameworks. This paper explores these elements, leveraging case studies to illustrate challenges, lessons learned, and best practices in CCS deployment worldwide.

Objective

The objective of this analysis is to evaluate the technological, environmental, and regulatory considerations associated with the safety of CCS projects. By assessing key components such as site selection, MMV strategies, and long-term stability, this study aims to identify best practices and highlight potential risks to ensure the safe and effective implementation of CCS systems. Case studies, including Shell Quest, In Salah, Weyburn, Salt Creek Field, and ADM Decatur, serve as practical examples to contextualize these issues and provide insights into real-world challenges and advancements in CCS.

Analysis & Case Studies

Site Selection & Characterization

The safety of a carbon storage sight is most directly related to the characteristics of the natural formation. There are 3 main underground formations that CO_2 can be stored in: (1) oil and gas reservoirs (2) deep coal seems (3) and saline aquifers. The first two allow for oil to be recovered in the storage process while saline aquifers do not. However saline aquifers allow for much more storage capacity. The safety benefits of (1) oil and gas fields are that for thousands of years they have contained crude oil or natural gas which is a demonstration of an effective seal. When CO_2 is injected into (2) coal seams, it is replacing the methane that is in the pours of the coal. Coal is highly porous and preferentially absorbs CO_2 which reduces the risk of the CO_2 migrating outside of the reservoir. However when coal absorbs CO_2 it expands, reducing the storage capacity, and increasing the risk of overpressure. Finally, (3) saline aquifers are similar to oil and gas reservoirs, however they do not have the proven cap rock seals that oil and gas reservoirs have (SECARB deliverables Vol I).

In all potential CCS sites there are a few key features that help determine the safety of the site. Those features are: the well depth, porosity and permeability, cap rock, proximity to faults and proximity to freshwater. Well depths are usually targeted to be greater than about 800 m below the surface. At this depth the CO_2 becomes supercritical. This increases the density of the CO_2 allowing for a larger amount to be stored in a smaller volume. Next, the goal is to maximize the porosity and permeability of the reservoir. The higher these values are the more area that will be available for storage and less risk for overpressure. Usually, reservoirs with sandstone are targeted because of their large porosity. On the other hand, reservoirs should have a cap rock that has a very low porosity and permeability. The cap rock is the main feature that prevents CO2 from migrating outside of the well. Clay and shale are good examples of cap rock materials that effectively trap CO2. It is extremely important that the cap rock spans the entire reservoir. Heterogeneities in the cap rock can create pathways that allow CO2 to escape from the reservoir. Other leakage pathways could also be faults. It is best practice to minimize the amount of faults that are near or in these reservoirs. Faults can be significant leakage pathways for CO2. Finally it is important for the reservoir to not be in contact with Underground Sources of Drinking Water (USDW). If CO2 contaminates USDWs, it can significantly raise the pH, harming people and animals that consume it.

Case Study: Shell Quest

For Shell's Quest CCS Project in Alberta, Canada, they adopted the IEA's (spell out 1st time) site selection criteria for ensuring the safety and security of CO2 storage. This is a quantitative framework for site criteria. The table below has been split into three criteria levels, critical, essential, and desirable. Each of the criteria then have an eliminatory/unfavorable condition and a preferred/favorable condition. However, this criteria list is not the final determinate of the safety of a site. Many tests and simulations must be run on a site before it can be deemed safe. But this table provides an initial framework for selecting potential sites.

		CO2 Storage Property or Attribute		
Criterion Level	No.	Criterion	Eliminate or Unfavourable	Preferred or favourable
Critical	1	**Reservoir Seal Pairs**, extensive and competent barrier to vertical flow	Poor discontinuous, faulted and/or breached	Intermediate and excellent, many pairs (multi-layered system)
	2	**Pressure** regime	Overpressure, pressure gradients greater than 14kPa/m	Pressure gradients less that 12 kPa/m
	3	**Monitoring** potential	Absent	Present
	4	Affecting **protected groundwater quality**	Yes	No
Essential	5	**Seismicity**	High	Moderate or less
	6	**Faulting & fracturing**	Extensive	Limited to moderate
	7	**Hydrogeology**	Short flow systems or compaction flow. Saline aquifers in communication with protected groundwater acquifers	Intermediate and regional scale flow
Desirable	8	**Depth**	<750-800m	> 800m
	9	Located within **fold belts**	yes	No
	10	Adverse **diagenesis**	Significant	Low to moderate
	11	**Geothermal** regime	Gradients >35 degC/km and/or high surface temperature	Gradients <35 degC/km and low surface temperature
	12	**Temperature**	<35 deg C	>35 deg C
	13	**Pressure**	< 7.5 Mpa	> 7.5 Mpa
	14	**Thickness**	< 20m	> 20m
	15	**Porosity**	< 10%	> 10%
	16	**Permeability**	< 20mD	> 20mD
	17	**Caprock** thickness	< 10m	> 10m
	18	**Well Density**	High	Low to moderate

Figure ___ is this table you creation, or reference needed?

Measurement, Monitoring & Verification

Once an appropriate site has been chosen it is important to apply measurement, monitoring and verification (MMV) technology to ensure the immediate and long-term stability and safety of a CCS site. MMV is used to monitor the reservoir area for any possible CO2 leaks, signs of seal failures or deviations from the intended injection area. It is crucial to use a wide range of these MMV technologies to have multiple layers of protection. Some commonly used MMV techniques used above ground are Interferometric Synthetic-Aperture Radar (InSAR), microseismic monitoring, electrical resistance tomography, surface sampling, Downhole Pressure-Temperature Gauges (DPTG), and tracers.

InSAR - A method using radar waves from a satellite to measure the deformation of the surface of the earth. It can measure surface deformations down to a millimeter. InSAR is useful in detecting reservoir overpressures that can cause the cap rock and surface to bulge. A downside is that InSAR requires careful data processing and geomechanical modeling. InSAR has been successfully used at the In Salah site to detect bulges in the surface.

Microseismic monitoring – Often many different devices, both above and below ground, are used to monitor seismic activity at sites. One of the main devices is a geophone string placed in wells to monitor for any small earthquakes that would be undetectable by humans. Above ground seismic surface nodes are used to record seismic data as well. Data from microseismic monitoring can reveal two things. It can detect small earthquakes that can indicate where the CO2 plume is migrating towards. It can also provide data of locations of potential undiscovered faults within a reservoir. This technology has been effectively deployed at the Shell Quest Site (Effective use of MSM).

Electrical Resistance Tomography – This technique uses a series of underground electric diodes that send electric currents into the ground. Those electric currents are then used to track the CO2 plume once it's underground. Similar to microseismic, this creates a model of the CO2 plume underground, however ERT is a more active way to measure the CO2 plume. This technology was developed and tested at the Ketzin CCS site.

Surface Sampling – One of the simplest ways to test for CO2 leaks. This simply involves taking groundwater and soil samples and testing their CO2 concentrations and pH's for any potential signs of leakage.

Downhole-Pressure-Temperature Gauges – These devices are placed both in the injection well as well as specific MMV wells. It is typical that many wells around the reservoir are created to measure and heterogeneities that may be present. These are the simplest underground measurements taken and are crucial to monitoring the stability and integrity of the well.

Tracers – These can be added to the CO2 being injected into the well. Commonly used tracers have been sulfur hexafluoride (SF6) and perfluorocarbons (PFCs). Tracers aid in the monitoring of CO2 plume migration and leaks by introducing these easily identifiable chemicals.

Case Study: In Salah

In Salah was a CCS site that pioneered the InSAR and 3D seismic technology. When used in conjunction with geographical modelling and 3D seismic data, it helped the operators track deformations in the Krechba reservoir. In 2008 the InSAR data indicated that there was an increasing risk of migration towards the north of the Krechba reservoir and possibly outside the hydrocarbon lease. In 2010 CO2 was detected at a well head that indicated a possible loss of well integrity. Finally, later in 2010, seismic data revealed new NW linear fractures aligned with the stress field. InSAR then indicated possible hydrofractures because of a 20mm deformation at the surface of the reservoir. In 2010 the decision was made to lower injection pressure but eventually in 2011, after additional analysis, the decision was made to suspend injection. In Salah is a great example of how multiple MMV technologies can be used to provide precise data on how CO2 reservoirs behave (Lessons Learned).

Environmental & Health Impacts

Storing CO2 underground comes with many risks, particularly to the environment and health of people. Unlike most other chemical processes where the process is designed to contain the chemicals, CCS relies on natural formations to contain the CO2. This means that these natural formations are not always perfect and pose many risks to leaking CO2 into the environment. A common practice in existing CCS sites is to divide the process area into separate areas of impact, define the consequences for each of the areas, and then develop MMV technologies or process improvements for those areas. The goal is to reduce the impact to the environment from both the injection process and the storage of CO2.

The Shell Quest focuses mainly on the environmental impacts of a loss of containment once the CO2 is underground. They divide the environment into four areas: (1) Hydrocarbon resources, (2) Groundwater impacts, (3) Soil contamination, and (4) CO2 emissions into the atmosphere. The hydrocarbon resources only apply if the CCS site is an EOR site. If it is, CO2 can increase the salinity or acidity of the produced fluids which can affect downstream production. The impacts to groundwater and soil would be similar. With an increase in CO2, the quality makes it less suitable for plant and animal life. Finally, the impact on the atmosphere would reduce the effectiveness of the project's contribution to climate change mitigation (Quest MMV Plan).

Other CCS projects such as the Illinois Basin – Decatur Project also looked at the environmental impacts of the injection process itself. For this project, they examined the effects of dust, noise, emissions and wildlife (Initial Risk Assessment). The injection process requires large diesel fuel pumps that create noise and can disturb wildlife. Another CCS project, SECARB, also focused on the entire injection process. They conducted a What-If analysis for each step of the project. For example, clearing a site of vegetation could lead to erosion of the soil which could cause sedimentation in nearby streams and harm stream species (Environmental assessment). While this isn't a direct effect of CO2 it is still an environmental impact that needs to be taken into consideration.

Overall, it is important that the environmental effects of CO_2 and the entire process must be considered. This ties in with other considerations such as site selection and MMV. To reduce the impact to the environment, locations should not be chosen too close to wildlife, humans or important ecological areas. Projects should also make sure that they have MMV technology in each of these areas to mitigate environmental impact.

Case Study: Weyburn Oil Field

The Weyburn Oil Field is located in southeastern Canada and has been an active oil field since 1954. In 2000, a company began to inject CO_2 into the Weyburn field for EOR. In 2010, property owners in the oil field noticed accumulations of algae, unsightly sheens, apparent CO_2 degassing, and dead animals around a pond on their property. Three separate companies conducted surveys on the land to determine the source of the strange events. It was eventually determined that there were elevated levels of CO_2 in the soil and water but that the source of the CO_2 was bacterial in origin. So, while the CO_2 injection and EOR was not the cause of the elevated CO_2 levels, Weyburn still serves as an example of the environmental dangers of CCS.

Long Term Stability & Integrity

When planning a CCS site, one of the biggest challenges is to be able to ensure the long term stability of the site. Geologists have tried to model the behavior of the underground reservoirs to predict how they will behave when the CO_2 is injected and after injection has ceased. But these models are not perfect, which makes it impossible to perfectly predict the future. From both research and actual incidents common failure modes or weak points can be identified to help narrow the scope of these long-term studies. Often these weak points are undiscovered faults, natural and man-made seals and monitoring wells. Causes of these weak points are usually well overpressure, use of improper material and incomplete well data. It is important that these parts of the process are closely monitored to ensure long term stability and integrity.

Of the cases studied, man-made seal failures were the most common type of CO_2 leak source. Man-made seals are usually made of concrete and corrosion resistant material. It is placed around the annulus of the injection well, as well as the monitoring wells. However, the installation of these seals is not always perfect and can lead to CO_2 leakage. Also, in instances such as Salt Creek Field, some wells are not created with corrosion resistant material.

Natural cap rock seals are also common locations for leaks. It is important to create a model of the reservoir to understand the cap rock formations and predict where the CO_2 will migrate to. If these geographical models are incomplete, they can often leave undiscovered permeability heterogeneities. These heterogeneities can change how the CO_2 migrates and create possible leakage pathways. Natural seals can also be damaged during the injection process. Overpressure during the injection process can cause excess strain on the cap rock seal. This can create faults that breach the low permeability layer and allow CO_2 to leak to the surface (Leakage Pathways).

Case Study: Salt Creek Field, WY

Salt Creek Field is CCS-EOR site that started injecting CO_2 in 2004. In 2016, an incident occurred that resulted in CO_2 and natural gas to leak from a wellbore. Salt Creek was discovered in 1889 and has since had more than 4,000 wells drilled into it. In 2016 about 3,000 of those wells were plugged and inactive. However, because of their long history, well data was incomplete, but what was known was that many of the plugged wells were not designed for corrosive CO_2. This led to the seal corrosion of an inactive wellbore located in the middle of a school yard. The inactive well was considered unproductive, abandoned and left unmonitored. The school was forced to close from elevated levels of CO_2. No injuries were recorded. Twenty tons of cement were pumped into the wellbore and air monitoring and ventilation systems were installed. Two lessons can be learned from this incident. Firstly, it is important to consider the surrounding environment when choosing where to install wellbores and other parts of the CCS process. Secondly, just because a wellbore is inactive does not mean that the risk of a loss of containment is zero. It is important to constantly monitor all potential leakage pathways and maintain the integrity of the seal (Leakage Pathways).

Regulatory & Safety Framework

Legal Framework has been developed to ensure the environmental safety of the CCS sites across the globe. The framework provides guidelines on site selection and characterization, allowable environmental impact, and minimum measurement, monitoring and verification techniques applied. Many countries have their won legal frameworks to help ensure the safety of the country. Complementary standards have also been developed to help support compliance with the legal frameworks.

In the US, the EPA has developed the Well Class VI regulation for CO_2 injection wells. The requirements include site characterization, prediction of the extent of the plume, MMV, proper plugs, financial responsibility, emergency response plans, and construction that prevents leaking or endangerment to human health. Often these regulations don't have quantitative requirements but rather the operator's ability to prove the safety of the well in each of the categories listed above. In Canada, there is no international organization that regulates CCS but many provinces have their own regulatory framework. In Australia, there are federal laws such as the Offshore Petroleum and Greenhouse Gas Storage Act 2006 that regulate offshore CCS. Similar to Canada, they also have specific states that have put in place regulations. In Victoria, there is the Greenhouse Gas Geological sequestration Act that governs land-based CO_2 storage. As well as legal regulations, some organizations such as the ISO, DNV and IEA, have developed complementary guidelines to assist operators comply with legal requirements and improve safety.

Since CCS is relatively new, particularly commercial sites and sites for storage only, many countries do not have a comprehensive legal framework. Many companies have opted to follow the certification framework of independent organizations because much more extensive research has been conducted and their methods proven. For example, the CO2SINK Ketzin project was a pilot project in Germany that helped develop and use the DNV regulatory framework. One of the many challenges in developing a comprehensive certification framework is that each project should be site specific and no two natural formations are the same. Overall, many countries are developing legal frameworks as they try to reduce their carbon emissions and make CCS a safer process.

Case Study: ADM Decatur

Archer- Daniels-Midland Co. is a CCS operator in Decatur, Illinois that had started the first commercial CCS site in the US. In March 202 ADM detected a leak, five months after they had detected corrosion in a monitoring well. However, they decided to keep the public and the EPA in the dark. ADM notified the EPA on July 31, 2024 and this information was not made known to the public until September 13, 2024, almost 6 months after the leak was detected (Grist). The EPA reported that they violated its Class VI Underground Injection Control permit when the injected fluid migrated into an unauthorized zone roughly 5,000 feet deep (EPA). The fluid migrated underneath Lake Decatur, a source of public water. However, the underground fluid is separated from the drinking water by about a vertical mile of rock and officials do not believe that it poses a risk to human health. The EPA also ruled that ADM failed to monitor the Class VI injection in accordance with the permit or follow an emergency response and remediation plan (Reuters). It is unclear whether it was illegal for ADM to with hold the reporting of the leak which emphasizes why it is so important to have a legal framework for CCS processes.

Conclusions

CCS represents a promising solution to global carbon emissions, but its effectiveness relies on meticulous planning, technological innovation, and robust regulatory oversight. The case studies examined reveal critical lessons about the importance of site selection, the role of MMV technologies, and the necessity of comprehensive frameworks to manage environmental and safety risks. While CCS has demonstrated success in projects like Shell Quest, incidents such as those at In Salah and ADM Decatur underscore the need for continued research, improved monitoring practices, and enhanced transparency. With a concerted effort to address these challenges, CCS can play a vital role in achieving a sustainable low-carbon future.

References