

The Permanence of Geological Carbon Storage

An Overview of Carbon Sequestration Methods

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Abstract

The reduction and removal of atmospheric CO₂ emissions is required to keep warming below 2 C. Carbon sequestration is a viable strategy to implement large-scale reduction and removal of emissions. There are numerous sequestration processes that vary from short-term and high risk (forestry methods, soil sequestration, and coastal blue carbon management) to long-term and low-risk (enhanced weathering and geological carbon storage). The permanence of carbon sequestration methods can be described by (i) duration of storage and (ii) risk of reversal. Geological carbon storage, the injection and containment of CO₂ in deep underground reservoirs, is often touted as a “permanent” process, but the possibility of CO₂ leakage of CO₂ from these formations raises concerns about the permanence of the process. To investigate the permanence of geological carbon storage (GCS) and other sequestration methods, a literature review was conducted. It was found that GCS can only store CO₂ indefinitely if no leakage occurs. Leakage occurs via (i) fractures or abandoned wellbores not addressed during site screening or (ii) improper pressure management during injection. The most significant threat to storage security is the abundance of abandoned or improperly sealed wellbores that compromise the integrity of the storage reservoir. The risk of leakage is reduced over time as CO₂ is immobilized by capillary forces, dissolved in reservoir fluid, or mineralized into a stable carbonate form. After injection, a variety of monitoring techniques exist to detect leakage from the reservoir. Ultimately, whether leakage occurs depends on the quality of GCS regulations in the region of implementation. Since regulatory frameworks vary from country to country, the permanence of GCS cannot be guaranteed. Furthermore, questions remain as to the economic viability of GCS as a large-scale climate mitigation tactic.

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1 Introduction

1.1 Justification

Anthropogenic activities, primarily through the emissions of greenhouse gases such as carbon dioxide (CO₂) have caused global warming, with surface temperature reaching 1.1 C above pre-industrial levels as of 2020¹. This has resulted in widespread adverse impacts on human health, food and water security, economies, and societies. The dominant anthropogenic sources of CO₂ include fossil fuel consumption, agriculture, cement production, and land use change are dominant anthropogenic sources². The Intergovernmental Panel on Climate Change (IPCC), among many other sources, has identified an urgent need to mitigate CO₂ emissions to keep global warming below 2 C above pre-industrial levels.

Climate change mitigation is the reduction of CO₂ emissions and/or removal of atmospheric CO₂. Carbon sequestration – the capture and storage of carbon dioxide (CO₂), can be a mechanism for both the reduction and removal of emissions. Carbon sequestration can be loosely categorized into processes that result in a net removal of atmospheric carbon (carbon dioxide removal/CDR), and processes that result in the reduction or prevention of CO₂ emissions (carbon capture and storage/CCS).

Although CDR is not a substitute for immediate and significant emissions reduction, it is part of all modelled scenarios that limit warming to 2 degrees or lower by 2100.³ CCS, the capture and storage of CO₂ from industrial or energy-related sources, is distinct from CDR in that it does not remove atmospheric carbon; it prevents certain industrial emissions from reaching the atmosphere, allowing those industries to reduce their emissions. Large-scale implementation of CCS is the only technology that may allow for continued large-scale industrial use of fossil fuels.

As stated by the IPCC, CDR methods are necessary for a net-zero future. However, whether CCS is a necessary and/or appropriate solution is much less clear. Proponents of CCS argue that a rapid transition away from fossil fuels is neither feasible nor realistic, and that CCS is a necessary technology during the transition to clean energy sources.⁴ Opponents of CCS argue that the significant resources required to implement large-scale CCS would be better used to transition to clean energies and avoid the extraction of fossil fuels in the first place.⁵

¹ Calvin et al., “IPCC, 2023.”

² National Academies of Sciences, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*.

³ Calvin et al., “IPCC, 2023.”

⁴ Bui et al., “Carbon Capture and Storage (CCS).”

⁵ Cameron and Carter, “Why Carbon Capture and Storage Is Not a Net-Zero Solution for Canada’s Oil and Gas Sector.”

Concerns associated with large-scale CCS implementation include its high cost, its capacity, the feasibility of large-scale implementation, and how permanent it is (among others).⁶ The question of whether or not CCS is a viable solution is broad and difficult to answer, and one that will not be answered in this report. Instead, this report will investigate just one of the associated concerns: permanence.

Questions of permanence are relevant not just for CCS; all carbon sequestration methods vary in permanence. Furthermore, global policy frameworks for carbon sequestration are fragmented and inconsistent, and there is no international definition of permanence⁷. Of specific concern is the assumption and assertion that certain carbon sequestration methods are “permanent” without reference to any specific definition or supporting evidence.

1.2 Objectives

The objectives of this report are as follows:

1. Summarize the permanence of various carbon sequestration processes:
 - a. Define permanence in the context of carbon sequestration
 - b. Present an overview of carbon sequestration methods in relation to the above definition of permanence
2. Investigate the permanence of geological carbon sequestration in particular:
 - a. Present an overview of geological carbon storage processes
 - b. Investigate the assumption that geological carbon storage is permanent
 - c. Draw conclusions about the permanence of geological storage and identify areas of further research

To achieve these objectives, a literature review was conducted. The results of this review are presented.

2 Carbon Sequestration

For the purpose of this report, the most recent IPCC definitions will be used. According to the IPCC, carbon sequestration is the process of storing carbon in a carbon pool. A carbon pool is a reservoir in which carbon resides for a period of time.⁸ In the context of climate mitigation, carbon sequestration refers to the storage of carbon in a reservoir other than the atmosphere via the anthropogenic enhancement, facilitation, or replication of natural sequestration processes.

Sequestration processes for climate mitigation include:⁹

⁶ Budinis et al., “An Assessment of CCS Costs, Barriers and Potential.”

⁷ Arcusa and Hagood, “Definitions and Mechanisms for Managing Durability and Reversals in Standards and Procurers of Carbon Dioxide Removal.”

⁸ Calvin et al., “IPCC, 2023.”

⁹ Ruseva et al., “Rethinking Standards of Permanence for Terrestrial and Coastal Carbon.”

- Afforestation/reforestation (AR)
- Soil carbon sequestration
- Biochar
- Coastal blue carbon
- Enhanced weathering (EW)
- Geological carbon storage (GCS)
- Carbon capture and utilization (CCU) in long-lived products

Sequestration processes that capture carbon from ambient air typically result in a net removal of CO₂ from the atmosphere. Net-negative processes are referred to as carbon dioxide removal (CDR). In comparison, GCS and CCU require a pure stream of CO₂. GCS is exclusively a storage mechanism and can be paired with a variety of carbon capture technologies. A pure stream of CO₂ can be obtained via direct air capture (DAC) which removes CO₂ from ambient air, or via combustion capture methods, which remove carbon from industrial and energy-related sources. Depending on where the carbon is sourced from, GCS can result in a removal of emissions or a reduction of emissions.

Each sequestration method retains carbon for a different period of time. Historically, sequestration methods were simply separated into impermanent storage (terrestrial) and permanent storage (geologic).¹⁰ However, as more and more sequestration strategies emerge, this definition has evolved over time.

2.1 Permanence

There is not one internationally accepted definition of permanence that applies to all sequestration methods.¹¹ Definitions vary from country to country, and in countries they vary between organizations. Furthermore, scientists and policymakers tend to use different terminology, leading to inconsistency in standards and regulations.¹² The permanence of a sequestration project can be described by two facets of that project: the storage duration and the risk of premature reversal.

The storage duration of a sequestration project is the amount of time that CO₂ will remain sequestered. Storage duration varies between sequestration methods and between individual projects. Duration is typically described by magnitudes of years (decades, centuries, millennia, etc.).

The risk of premature reversal is distinct from the duration of a sequestration project. Risk of premature reversal refers to how vulnerable a carbon pool is to events that result in reversal and

¹⁰ Arcusa and Hagood, “Definitions and Mechanisms for Managing Durability and Reversals in Standards and Procurers of Carbon Dioxide Removal.”

¹¹ Mac Dowell, Reiner, and Haszeldine, “Comparing Approaches for Carbon Dioxide Removal.”

¹² Arcusa and Hagood, “Definitions and Mechanisms for Managing Durability and Reversals in Standards and Procurers of Carbon Dioxide Removal.”

CO₂ emissions. For example, the duration of reforestation projects sequestration is decades to centuries, but risks of premature reversal such as forest fire and drought make AR a relatively vulnerable method.¹³

In literature, terminology is inconsistent, but the “permanence” of a project typically refers to its storage duration, whereas the “durability” of a project may encompass both storage duration and risk of reversal. “Permanence” and “durability” are often used interchangeably.¹⁴ This report will use the terms “storage duration” and “risk of reversal” to describe permanence.

2.2 Overview of Sequestration Methods

2.2.1 Afforestation/Reforestation (AR)

Afforestation refers to the foresting of land that did not historically host forest. Reforestation refers to the conversion of land to forest that has historically contained forests.¹⁵ Vegetations remove CO₂ from the atmosphere via photosynthesis and store it in living biomass, dead organic matter, and soils.¹⁶ Once CO₂ is sequestered by forests, it can be retained for decades to centuries, depending on management practices. In fact, AR requires continuous management, so the permanence of a project typically depends on the contractual obligation of the storage operator.¹⁷

However, AR is one of the least secure sequestration methods; disturbances to the forest such as deforestation, drought, and wildfire can rapidly release the stored carbon.¹⁸ Related sequestration methods include agroforestry and peatland restoration.¹⁹

2.2.2 Soil Carbon Sequestration

Soil carbon sequestration refers to the storage of CO₂ in soil systems as soil organic matter.²⁰ Soil carbon sequestration is facilitated by management practices such as reduced tilling, erosion control, addition of fertilizers, and use of cover crops. Soil carbon sequestration lasts for decades to centuries but is not very secure as changes in management practices can result in the loss of sequestered carbon.²¹

¹³ Ruseva et al., “Rethinking Standards of Permanence for Terrestrial and Coastal Carbon.”

¹⁴ CarbonBetter, “Permanence Considerations When Buying Carbon Credits.”

¹⁵ Calvin et al., “IPCC, 2023.”

¹⁶ Chiquier et al., “The Efficiency, Timing and Permanence of CDR Pathways.”

¹⁷ Ruseva et al., “Rethinking Standards of Permanence for Terrestrial and Coastal Carbon.”

¹⁸ Chiquier et al., “The Efficiency, Timing and Permanence of CDR Pathways.”

¹⁹ Calvin et al., “IPCC, 2023.”

²⁰ Dynarski, Bossio, and Scow, “Dynamic Stability of Soil Carbon.”

²¹ Dynarski, Bossio, and Scow.

A related sequestration method is biochar. Biochar refers the process of turning CO₂ into charcoal and adding it to soils to increase fertility, nutrient retention, and water-holding capacity.²² Biochar is notable for its permanence, but there are large knowledge gaps.²³

2.2.3 Coastal Blue Carbon

Coastal blue carbon is the oceanic equivalent of AR and soil C sequestration (terrestrial methods). Coastal blue carbon involves management practices that encourage sequestration in mangroves, seagrasses, and tidal marshes. It lasts decades to centuries, but relies on continuous management practices. Risks of reversal include pollution, coastal development, and degradation of coastal ecosystems.²⁴

2.2.4 Surficial Mineralization/Enhanced Weathering (EW)

Carbon mineralization is the process by which carbon is turned into a stable mineral like a carbonate.²⁵ There are three types of carbon mineralization in the context of climate mitigation: surficial mineralization, in-situ mineralization, and ex-situ mineralization. They are distinct in how they source carbon and where they store carbon but share the same underlying chemistry.²⁶

Surficial mineralization (also called enhanced weathering or EW) is the sequestration of ambient CO₂ via feedstock (minerals with the capacity to sequester CO₂) that is crushed and spread over fields and coasts.²⁷ Surficial mineralization has the potential to store carbon for many millennia and is a very secure form of sequestration, as it would require reverse engineering to reverse the mineralization process.²⁸

2.2.5 Carbon Capture and Utilization (CCU)

Carbon capture and utilization is the usage of captured carbon for industrial purposes such as enhanced oil recovery (EOR) or as a resource in the food and beverage industry (e.g. carbonization of soft drinks). Carbon utilization can also result in sequestration if carbon is stored in long-lived products. The best example carbon utilization as a form of storage is ex-situ mineralization, a form of mineralization where a pure stream of carbon reacted with mined rocks to form benign minerals such as carbonated concrete that can be used in construction. The duration of CCU depends on the product, but typically lasts 100,000+ years with little to no risk of reversal.²⁹

²² Li and Tasnady, "Biochar for Soil Carbon Sequestration."

²³ Ruseva et al., "Rethinking Standards of Permanence for Terrestrial and Coastal Carbon."

²⁴ Calvin et al., "IPCC, 2023."

²⁵ Riedl et al., "5 Things to Know About Carbon Mineralization As a Carbon Removal Strategy."

²⁶ Raza et al., "Carbon Mineralization and Geological Storage of CO₂ in Basalt."

²⁷ Riedl et al., "5 Things to Know About Carbon Mineralization As a Carbon Removal Strategy."

²⁸ DePaolo and Cole, "Geochemistry of Geologic Carbon Sequestration; an Overview."

²⁹ "Permanence in Carbon Credits: Why It Matters, and How to Evaluate It."

2.2.6 Geological Carbon Storage (GCS)

Geological carbon storage is the injection of a pure stream of CO₂ into an underground reservoir. GCS is exclusively a storage method that can be paired with different carbon capture technologies. Although the capture method used in GCS is not crucial to discussions of permanence, it is crucial to discussions of cost and viability, making the terminology of carbon capture relevant.

There are clear distinctions between the different forms of GCS depending on where the carbon is sourced from. Carbon Capture and Storage (CCS) is GCS implemented with CO₂ captured from industrial and energy-related point sources, typically by post-combustion capture. CCS only results in a reduction of CO₂ emissions, not a removal of CO₂ from the atmosphere. Direct air carbon capture and storage (DACCS) is GCS implemented with CO₂ captured from DAC³⁰. DACCS results in a net removal of atmospheric CO₂. Bioenergy with CCS (BECCS) a larger process in which CO₂ is captured and utilized as a biofuel, and that biofuel is then combusted and paired with combustion-related capture methods to capture and store the carbon. BECCS results in a net removal of CO₂.³¹

Most literature refers to GCS as a “permanent” process without elaborating on the meaning of “permanent”. Lexically, a “permanent” process is one that lasts indefinitely, or to infinity. Applying this term to GCS without a concrete definition of what constitutes “permanent” constitutes a fairly large unsubstantiated claim, and ones that this report investigates.

Although GCS has the definite potential to store carbon for millennia, if not millions of years,³² calling it permanent implies that the reservoir will stay as it is for all time (which, on a geological timescale, is not practical), and implies that there is no risk of premature reversal. In GCS, the risk of reversal is equivalent to risk of leakage. Leakage mechanisms will be investigated to determine whether or not this risk is substantial.

2.3 Summary and Comparisons

Table 1 presents a summary of the above discussion, with data sourced from the IPCC fact sheet on CDR methods.³³ It should be noted that this table includes the most prominently discussed and/or viable methods of carbon sequestration that are considered in literature at this time. There are other sequestration methods that have been deemed impractical and/or unviable at this time, such as deep ocean sequestration – a form of sequestration where CO₂ is injected into deep ocean trenches that results in ocean acidification, which is undesirable. Additionally, there are

³⁰ Calvin et al., “IPCC, 2023.”

³¹ Chiquier et al., “The Efficiency, Timing and Permanence of CDR Pathways.”

³² Celia, “Geological Storage of Captured Carbon Dioxide as a Large-Scale Carbon Mitigation Option.”

³³ Calvin et al., “IPCC, 2023.”

emerging methods whose viability remains to be seen. As such, this list does not provide a comprehensive history of sequestration methods, but rather a snapshot of current practices.

Table 1: Summary of sequestration processes and the comparison between them.

Sequestration Process	Permanence (years)	Risk of Premature Reversal	Cost (USD per tonne of CO ₂)
AR	10s – 100s	Moderate to high	0-240
Soil sequestration	10s – 100s	Moderate to high	45-100
Biochar	100s – 1000s	Low	10-345
Coastal Blue Carbon	10s – 100s	Moderate to high	(Not enough data)
Enhanced Weathering	10,000+	Low	
CCU	100,000+	Low	(Not enough data)
GCS	10,000+	Low	DACCS: 100-300 BECCS: 50-200

3 Stakeholder Analysis

In the pursuit of mitigating climate change, carbon capture and storage as well as carbon capture utilization and storage technologies have emerged as a potential solution for reducing greenhouse gas emissions. In industries such as oil and gas, significant carbon emissions are generated and emitted from point sources. When addressing this topic in the Canadian economic, environmental, and social landscape, there are key stakeholders for whom the use of CCS/CCUS can either be advantageous or disadvantageous. This stakeholder analysis will address four key stakeholders regarding the use of Carbon Capture and Storage and their overall perspective on this technology.

3.1 Oil and Gas Companies

Oil and gas companies are significant stakeholders in CCS initiatives due to their involvement in creating substantial carbon emissions. Carbon can be captured from industrial processes, such as oil refineries and natural gas processing plants, adding to their stake in the technology. It is then transported from these facilities through pipelines to designated storage sites. Companies in Canada are also responsible for monitoring storage sites and are tasked with reporting any carbon leakage witnessed in their facilities. Their motivations to engage in CCS include complying with federal and/or provincial regulations, mitigating emissions, and improving their reputation in connection with adhering to corporate social responsibility standards.

To provide an example of the oil and gas industry's involvement in CCS projects in Canada, [Carbon Engineering](#) can be highlighted. This company specializes in Direct Air Capture (DAC) technology, which directly removes carbon dioxide from the atmosphere in comparison to

directly from industrial plants³⁴. They have gained investment in the private and public sectors, allowing them to continue funding future projects.

3.2 Public

Public opinion is crucial in terms of shaping government policies and industry practices regarding CCS projects. Without a high level of public support or with the public attempting to oppose the development of CCS technologies, the feasibility and acceptance of CCS projects can be impacted. Public perception regarding the environmental, social, and economic implications is crucial in determining the success of CCS³⁵. Without large amounts of support, investments decrease, the number of those willing to work on CCS projects decreases, and government trust is decreased.

Environmental organizations are a great way to engage with the public. A organization highlighted on the government of Canada's website is The [Pembina Institute](#), this organization exemplifies a great advancement in public engagement; they advocate for sustainable energy policies and provide research and analysis on CCS technologies and their potential to mitigate climate change³⁶. It allows the public to be further informed on the topic, allowing their opinion to be backed by researched knowledge on the topic.

3.3 Indigenous Peoples

Indigenous peoples in Canada have a significant stake in projects regarding Carbon Capture and Storage. The Indigenous community has a strong tie to the preservation of land as the protection of the environment is an integral value that is held amongst their communities. Climate change affects the quality of life for many indigenous peoples, as the reliance on land and preservation of natural resources are key in providing for those in the community³⁷. Due to climate change and pollution, the following have already disrupted the First Nation communities:

- Mercury-poisoned fish because of water pollution leading to incurable health issues.³⁸
- Climate change being a factor in wildlife extinction, limiting the community's ability to hunt³⁹.
- Rising sea levels and storms leading to the destruction of nearby reserves and communities⁴⁰.
- The instability of the environment leading to changes in traditional environmental practices for new generations, taking away more history from the indigenous community⁴¹.

³⁴ "Carbon Engineering | Direct Air Capture of CO2 | Home."

³⁵ L'Orange Seigo, Dohle, and Siegrist, "Public Perception of Carbon Capture and Storage (CCS)."

³⁶ Institute, "Clean Energy Think Tank."

³⁷ "Canada's 'Indigenous Advantage' in Carbon Capture and Storage."

³⁸ "Environmental Protection & Climate Action - Assembly of First Nations."

³⁹ "Environmental Protection & Climate Action - Assembly of First Nations."

⁴⁰ "Environmental Protection & Climate Action - Assembly of First Nations."

⁴¹ "Environmental Protection & Climate Action - Assembly of First Nations."

There is a necessity to work alongside the indigenous community as 80% of the world's natural life resides on indigenous lands and territories⁴²; most of the pipelines and storage sites used to transport and store captured CO₂ emissions would reside on or near this land. As preservation of land is crucial to the First Nations community, it is essential to work alongside them to create solutions that would mitigate climate change for all, while posing less risks to those in proximity that rely on natural resources⁴³.

In the United Nations Declaration of Rights of Indigenous Peoples, there is a strong emphasis on ensuring that all indigenous peoples have the right to maintain their local affairs and essentially conserve their land and practices, which CCS projects have the potential to not adhere to if cooperation is not met on both parties.

In 2023, the government of Alberta acted in engaging with Indigenous communities in preparation for incoming CCS projects in the Edmonton region⁴⁴. The main First Nations communities are comprised of the four Treaty 6 First Nations, they are:

- The Alexander First Nation
- Alexis Nakota Sioux First Nation
- Enoch Cree First Nation
- Paul First Nation

In 2022, one of the major gas companies, [Enbridge](#), partnered in a treaty agreement with Four Treaty 6 First Nations to unveil the [Open Access Wabamun Carbon Hub](#)⁴⁵. This treaty allows other First Nation communities to unite in future developments of CCS projects. Like [Enbridge](#), [Wolf Midstream](#), a pipeline company, and [Whitecap Resources](#), an oil company, also signed a contract with the same Four Treaty 6 First Nations on a separate CCS site in the same geographic area⁴⁶.

Other than the justification of preserving land and mitigating climate change, one of the driving factors of working with indigenous communities, for these large corporations, is that it allows project proposals for CCS hubs to be given a greater chance of acceptance. One of the requirements in the Government of Alberta's business model is that there should be a display of benefit to Indigenous communities⁴⁷. The reasoning for this is that it allows an equal opportunity for indigenous communities to not only repair the environment and preserve traditional practices that climate change has taken away from, but it allows a larger incentive for economic

⁴² "Environmental Protection & Climate Action - Assembly of First Nations."

⁴³ "Canada's 'Indigenous Advantage' in Carbon Capture and Storage."

⁴⁴ "Canada's 'Indigenous Advantage' in Carbon Capture and Storage."

⁴⁵ "Canada's 'Indigenous Advantage' in Carbon Capture and Storage."

⁴⁶ "Canada's 'Indigenous Advantage' in Carbon Capture and Storage."

⁴⁷ "Canada's 'Indigenous Advantage' in Carbon Capture and Storage."

participation amongst the First Nation communities⁴⁸. The government of Alberta aims for benefits such as employment, skills from employment, partnerships, and further business development.

Indigenous Communities, such as those in Saskatchewan, view CCS with high amounts of potential due to the novelty of the technology and its advancements. With the advocacy for indigenous participation, further development is being created by these First Nation communities to benefit all.

The precedence of involvement that has been already created by the Government of Alberta can be a great stride that other governments may follow. By doing so, this allows benefits towards all stakeholders, as the guidance and support from those who weigh the environment on a higher pedestal than financial gain allow different lenses to a permanent solution.

3.4 Government

Carbon capture and storage is only one of the potentially viable solutions to mitigating greenhouse gas emissions and repairing the damages that are a consequence of climate change. As one of the key stakeholders, the Government of Canada plays a crucial role in shaping policies, regulations, investments, and partnerships related to the development of CCS technologies. The regulations may vary by province; however, the goal of the country is to achieve net zero emissions by 2050⁴⁹.

The Government of Canada has recently implemented the [Energy Innovation Program](#) that funds projects allowing Canada to make the necessary advances toward achieving the net zero goal. One of the categories of projects that organizations can apply for funding includes Carbon Capture and Storage projects. Additionally, the Government of Canada has promised to allocate \$319 million through their budget released in 2021. This allocation of funding is committed until 2028⁵⁰.

This report delves deeper into the regulatory framework and standards. However, to provide an overview, the regulations are enforced to predict the long-term effects on the environment that certain projects may cause. In terms of the federal government, there is an Environmental Assessment (EA) administered when addressing environmental initiatives. The assessment includes the following steps as provided by Project Pioneer and is administered by the [Canadian Environmental Assessment Agency](#)⁵¹:

- Identify possible environmental effects of a project.
- Propose measures to mitigate adverse effects.

⁴⁸ “Canada’s ‘Indigenous Advantage’ in Carbon Capture and Storage.”

⁴⁹ Canada, “Net-Zero Emissions by 2050.”

⁵⁰ Canada, “Energy Innovation Program - Carbon Capture, Utilization and Storage RD&D Call.”

⁵¹ Canada.

- Predict whether there will be a significant adverse environmental effect, even after the mitigation is implemented.
- Identify cumulative effects.

As Alberta is the province with the most CCS project development, its regulations are more refined, yet subject to change in adaptation to technological advancements. The areas that Alberta's jurisdiction reviews include Regulatory, Environmental, Geological Considerations, and Monitoring of sites. The focus of the framework provided by the government of Alberta is shown in Table 2⁵².

Table 2: List of frameworks and details on each.

Type of Framework	Focus of Framework
Regulatory Framework	<ul style="list-style-type: none"> • Approvals/permits • Site closure certificates • Transfer of responsibility • Post-closure stewardship fund • Pore space open access • Pipeline open access. • Landholder and public consultation • Surface access rights
Environmental Framework	<ul style="list-style-type: none"> • Environmental assessments • Safe transport of CO2 • CO2 composition and classification • Surface and subsurface reclamation and mitigation plans • Mitigating effects of CO2 emissions on air, land, and water.
Monitoring Framework	<ul style="list-style-type: none"> • Monitoring, Measurement, and Verification of <ul style="list-style-type: none"> ○ Pre-operational ○ Operational ○ Closure • Post-closure • Risk assessments. • Requirements for enhanced oil recovery sites that would like to act as storage sites.
Geological Framework	<ul style="list-style-type: none"> • Site selection criteria • Well construction • Operations • Abandonment • Closure assessment criteria

⁵² “An Integrated Risk Assessment and Management Framework for Carbon Capture and Storage.”

As displayed, the criteria established by the government of Alberta prove to be well-rounded in assessing risks with the goal of having CCS/CCUS be a permanent and safe solution. However, this can be subject to change with the further establishment of CCS projects in different areas of Canada. Each province will have its own set of refined regulations in accordance with their landscape. However, the main goal is to ensure safety among everything, ensuring there is mitigation in regard to future risks, and that is clear in the framework acknowledged by the Government of Alberta.

4 Carbon Capture

There are several ways of capturing CO₂. The main methods of carbon capture include capturing CO₂ under an industrial context which will be discussed in detail below, direct air capture and bioenergy capture. Capturing CO₂ under an industrial context will be the focus as this prevents the CO₂ from being released into the atmosphere whereas direct air capture and bioenergy capture it from the atmosphere.

4.1 Capture Methods

There are 3 main types of carbon capture in energy production and industrial facilities: Pre-combustion, post-combustion and oxy-fuel combustion.⁵³ These carbon capture methods all occur during the burning of fossil fuels industrial facilities, but at different stages. In general, capturing CO₂ will involve the separation of CO₂ from the flue gas produced from burning fossil fuels. Although capturing CO₂ increases operation costs, further research, and development may drastically lower the cost of capturing CO₂.

Post-Combustion Capture typically utilize solvents, solid sorbents, and membrane-based technologies. The solvents chemically absorb the CO₂ and are separated later on. Whereas Pre-Combustion Capture typically utilizes solid sorbents to capture carbon via chemical and/or physical adsorption. Membrane-based capture uses permeable or semi-permeable materials to produce a highly concentrated CO₂ stream which is captured. Oxy-Combustion Capture typically combusts a fuel in an oxygen rich environment to make carbon capture easier.

4.2 Compression and Supercritical CO₂

Compression must take place for CO₂ to be transported and injected into a storage site effectively. CO₂ must be compressed to about 1500 to 2200 psi and then cooled. When CO₂ is compressed, it becomes very hot so it must be cooled afterwards to be effectively transported and injected into a storage site as a supercritical fluid. The main way of compressing CO₂ is a centrifugal Compressors⁵⁴, but there are more advanced methods being researched such as:

⁵³ "Literature Survey of Carbon Capture Technology," n.d.

⁵⁴ "Literature Survey of Carbon Capture Technology."

- Isothermal CO₂ compression using liquid piston within integrated gas cooler
- CO₂ compression with supersonic technology⁵⁵

Super critical CO₂ is carbon dioxide that has been compressed to a supercritical state defined as at least a pressure of 74 bar and a temperature above 31 Celsius.⁵⁶ 74 bar is equivalent to about 1100 psi, which will then be compressed to 1500 to 2200 psi in a conventional compressor. This state is where the supercritical CO₂ behaves like both a gas and liquid.⁵⁷ They have surface tensions similar to gas and viscosities similar to liquids.⁵⁸

Since supercritical CO₂ is pressurized, it becomes much denser compared to its gaseous state. This allows for an efficient means of transporting supercritical CO₂ for storage. For example, if a natural gas pipeline meets the requirements to transport supercritical CO₂, (factors such as pressure rating), it repurposed for transporting supercritical CO₂, the density of supercritical CO₂ allows for the transport of much more supercritical CO₂ compared to natural gases. Depending on conditions, supercritical CO₂ can have a density of around 164kg/m³ to 941kg/m³⁵⁹ whereas natural gases have a density of 0.68kg/m³.⁶⁰

4.3 Cost

An estimate was done by the International Energy Agency in 2011. These results are a starting point and will most likely be different today, but in OECD countries, the overnight costs of these methods (the cost right now, without adjustment for inflation), calculated in 2011, estimates about 3800USD/kW for pre, post and oxy combustion for coal plants.⁶¹ This would imply that to build all the necessary infrastructure, it would take 3800 USD to capture a kilowatt worths of carbon from coal.⁶² A more recent analysis conducted for the northeastern and midwestern United States reported the cost at around \$52-\$60 per ton of CO₂ for coal based plants and around \$80-\$90 for natural gas plants.⁶³ This 10 year difference presents a much better result and cost figure as CCS technology has been researched and developed throughout the years.

⁵⁵ "S-Saretto-DresserRand-CO2-Compression-with-Supersonic-Tech.Pdf."

⁵⁶ "Club CO₂ - CO₂ Transport."

⁵⁷ "Supercritical Fluids – SCFCan."

⁵⁸ "Supercritical CO₂ Tech Team."

⁵⁹ "Supercritical Fluids – SCFCan."

⁶⁰ d.o.o, "Plinovodi - About Natural Gas."

⁶¹ "Cost and Performance of Carbon Dioxide Capture from Power Generation."

⁶² "Cost and Performance of Carbon Dioxide Capture from Power Generation."

⁶³ Schmelz, Hochman, and Miller, "Total Cost of Carbon Capture and Storage Implemented at a Regional Scale."

5 Transportation

After CO₂ is captured, there are a few transportation options to be considered. The main ones are the pipeline, truck and rail, and sea.⁶⁴ With these options, there are several challenges that are associated with them, such as risks and its usability which will be discussed under their respective sections.

One of the main challenges with CO₂ transportation is the costs associated with it. To transport CO₂, it must be compressed, but the degree to which it is compressed depends on how it is transported. With this, the cost of compression will vary heavily depending on how it is transported. Additionally, the transportation methods all have different costs associated with them. With pipelines, there is the cost of determining where the pipeline should be built, sourcing the materials, building the pipeline, and validating the pipeline. With truck and rail, there is the cost of sourcing and building the containers for transporting supercritical CO₂, the trucks/railcars and the energy spent transporting the CO₂, which is one of its main drawbacks. Burning fossil fuels and producing CO₂ to transport CO₂. With transportation by boat/sea, there is not a definitive cost for transporting by sea, as it is still in its infancy and ship designs are still being researched.⁶⁵

5.1 Pipeline

Pipelines for CO₂ are the most economical and efficient method of transportation. There's existing infrastructure for CO₂ that can be utilized and is regulated by the Department of Transportation's Pipeline Hazardous Material Safety Administration.

Currently, CO₂ pipelines have and are still being developed on land and under the sea. These pipelines have the same amount of risk as natural gas and oil pipelines, which makes CO₂ pipelines just as safe as these pipelines.

Transportation of supercritical CO₂ via pipeline poses the least number of challenges, as our research and infrastructure for natural gas and oil pipelines already exist. This allows us to project the already discovered and researched risks of natural gas pipelines to CO₂ pipelines. One of these risks can include a pipeline rupturing and its contents leaking into the ground and environment. This would result in adverse effects on the environment and human health. The specific effects will be discussed in a later section.

There are two main types of pipelines, underwater and land pipelines. As the names suggest, the underwater pipelines are constructed underwater and land pipelines are constructed on land, underground. Both pipelines are subject to regulations, but their construction processes are extremely similar to the way hydrocarbon pipelines are constructed.

⁶⁴ "Fact-Sheet-Transporting-Co2.Pdf."

⁶⁵ "Srccs_chapter4-1.Pdf."

For both pipelines, they also both face similar regulations but also have differences due to the nature of the environment they are constructed in. Pipelines are subjected to approval processes that include route path, inspection procedures, emergency response plans, and in more densely populated areas, it will be a more rigorous approval process. However, existing hydrocarbon pipelines can be converted to CO₂ pipelines, as they have similar regulations to CO₂ pipelines. This will happen under certain conditions, such as the pipeline being able to withstand a certain pressure. Should the pipeline be converted, the CO₂ will most likely be transported as a gas.⁶⁶ Pipelines that are operational are subjected to monitoring, internally and externally. Internal monitoring is done by internal pipeline inspection devices (pigs) and externally by monitoring and leakage detection systems. For land pipelines, the location of the pipeline will be considered, since failure of a pipeline in a sparsely populated area will most likely have less hazard to human life compared to failure in an urban area. However, the environmental damage will be large regardless of where it is since it is releasing vast amounts of CO₂ back into the atmosphere and surrounding ecosystem. The damage on these ecosystems could potentially be catastrophic for some species such as clownfish and their ability to find a suitable habitat.

From these regulations, pipelines also have a risk of failure, and the results of failure will vary on different factors. The main method of failure for these pipelines are ruptures and damage from outside forces. Outside damage can come from various things, such as construction equipment damaging land pipelines. Underwater, outside damage mainly comes from ships and debris. For example, ship anchors hitting the pipeline or ships that sink on the pipeline. Although unlikely and can be mitigated by trenching the pipeline (burying it under the sand), it can still happen. Another factor, common for land and underwater pipelines is corrosion. Corrosion can occur from the outside as well as the inside of the pipeline. Overtime, corrosion can occur due to several factors, such as the environment surrounding the pipeline as well as the supercritical CO₂ travelling inside the pipeline.⁶⁷

5.2 Truck

Transport by truck or rail is possible, but only in small quantities and very unlikely to be used. Truck use will only most likely be used to transport the already captured and pressurized CO₂ during a transition phase. For example, from a pipeline to pressurized cylinders or to an injection site. However, transportation via trucks poses massive risks. Some of these risks include accidents on the road, defective storage containers and human error. Most of these risks will result in the leakage of CO₂ back into the atmosphere which defeats the purpose of capturing it in the first place. However, the consequences of this can result in death in different ways. As the CO₂ is pressurized, it can be prone to explosion should the storage containers are defective. The amount of CO₂ present can cause asphyxiation should there be leakage and the CO₂ will displace

⁶⁶ Blackburn, "Risks of Converting Natural Gas Pipelines to CO₂ Service."

⁶⁷ "Srcs_chapter4-1.Pdf."

the surrounding oxygen present.⁶⁸ As a result, shipping supercritical CO₂ via truck is not a viable option.

5.3 Boat

Transportation by boat is in its infancy stage and more efficient methods are being developed for transportation by ship. However, from what we have right now, there are three types of tank structures for CO₂ transport by ship: pressure, low-temperature and semi-refrigerated. Pressurized transportation is designed to prevent the CO₂ from boiling and evaporating under normal atmospheric pressure. Low-temperature transportation has the same end goal in mind, to keep the CO₂ under a supercritical state and to prevent it from boiling. The semi-refrigerated method is the most versatile out of the three methods, as it combines the two methods mentioned above to accommodate for a wider range of ambient conditions and pressures.⁶⁹ However, with transportation by ship, there are instances where ships can sink, or become stranded or an accident happens such as a collision. These risks pose an extreme danger to everything and everyone surrounding the ship. An explosion with supercritical CO₂ would be disastrous and extremely lethal. As a result, although better than truck or rail, transportation by ship is also not a very viable option.

5.4 Leakage

Leakage can occur in all the transportation methods mentioned above. However, there are significantly more leakage risks with shipment by land and sea compared to pipelines. With trucks and rail, the road and rails can be bumpy or uneven, and the very motion of driving will cause vibrations in the vehicle or cargo container. This could result in unnecessary collisions within the vehicle and movement which could result in a rupture and a leak. A leak with supercritical CO₂ will cause severe consequences such as death and ecological destruction as the CO₂ is under intense pressure.

Leakage in transportation by sea also poses several issues/causes for leakage. These can include but are not limited to collision, stranding and fire. All of these scenarios can and most likely will cause the same magnitude of destruction as mentioned above from transportation by land. When a ship collides with something, the damage may be very minor, or it can be extreme like the explosion in Halifax in 1917. Or when a ship becomes stranded for any reason, the infrastructure needed to maintain the supercritical CO₂ could also fail, which would result in a catastrophic scenario. In the case of a fire on a ship, the heat from the fire would pressurize the storage containers such that the supercritical CO₂ could explode. All of these scenarios would be a catastrophic and disastrous outcome, making transportation by ship not very practical.

Shipping by pipeline is currently the most reliable method. Pipeline failures and leakages are relatively rare compared to the other two transportation methods. Pipeline transportation by marine pipeline is an example of pipeline reliability. One of the main mechanisms of marine

⁶⁸ "Srccs_chapter4-1.Pdf."

⁶⁹ "Srccs_chapter4-1.Pdf."

pipelines failing is very heavy debris falling on it. Such as ships sinking or ship anchors landing on the pipeline. Even though the mechanical failure rate of pipelines is very small compared to trucks or ships, the leakage rate has yet to be assessed on a mass scale.⁷⁰

5.5 Costs

The costs associated with transporting supercritical CO₂ can vary based on the method. For pipelines, there are construction costs that can include material/equipment costs, installation costs, operation and maintenance costs and other various costs such as regulatory filing fees, insurances costs, right-of-way costs etc. Transportation by sea has the cost of the ship, loading and storage facilities.⁷¹

Given these factors, a rough estimate was conducted for transportation by boat and pipeline at different distances indicated in Table 3.⁷²

Distance	Pipeline	Ship
100km	\$4 per ton	\$21/ton
500km	\$18 per ton	\$24/ton
1000km	\$31 per ton	\$27/ton

Table 3: Rough estimate for transportation over varying distances for both ships and pipelines.

The costs in the table above are represented in USD. The cost of a pipeline increases at a higher rate than ships. However, the practicality of a pipeline compared to a ship is a more valuable aspect of pipeline transportation. When transporting supercritical CO₂ to a storage site, a pipeline will most likely be used as the CO₂ will most likely be captured within the same country, so shipping by boat will be unnecessary. In the case of cross continental capture, such as Europe to North America, shipping supercritical CO₂ by boat may be necessary depending on what technology and infrastructure is readily available.

6 Geological Carbon Storage

Geological carbon storage (GCS) is the injection of CO₂ into deep geological formations. It is typically a component of the CCS process but can be implemented with CO₂ captured from direct air capture or as part of the BECCS process.

⁷⁰ "Srccs_chapter4-1.Pdf."

⁷¹ "Literature Survey of Carbon Capture Technology," n.d.

⁷² "Shipping and Offshore Pipeline Transportation Costs of CO₂ by Distance – Charts – Data & Statistics."

6.1 Suitable Geological Media

In general, there are two fundamental conditions that need to be met for a geological formation to be suitable for carbon storage:

1. Capacity and Injectivity

a. Capacity

A site must be able to store the intended volume of CO₂.

b. Injectivity

Injectivity is the ease fluids can flow through stratigraphic intervals⁷³, and the injectivity of a formation corresponds to the rate at which CO₂ can be injected into a site. To meet injectivity requirements, a site must be able to accept CO₂ at the rate it is supplied from the industrial point source.⁷⁴

2. Containment

A site must be able to permanently contain the injected CO₂ within the confinement zone without leakage into overlying units, groundwater, soil, or the atmosphere⁷⁵. Reservoirs that satisfy containment requirements are equivalently referred to as having an effective geological seal.⁷⁶

Formations that satisfy capacity and injectivity requirements are typically porous, permeable, sedimentary rocks⁷⁷ such as sandstone, limestone, and dolomite⁷⁸, but some igneous rocks such as basalt satisfy these requirements⁷⁹. Crystalline and metamorphic formations do not satisfy these requirements, as their low porosity and permeability would result in fracturing and faulting during injection⁸⁰. Although igneous formations are not usually suitable for CCS, porous rocks like basalt have potential to be used in mineralization operations. Literature focused on CCS in sedimentary formations may explicitly consider porosity and permeability to be fundamental

⁷³ Raza et al., "A Screening Criterion for Selection of Suitable CO₂ Storage Sites."

⁷⁴ Celia, "Geological Storage of Captured Carbon Dioxide as a Large-Scale Carbon Mitigation Option."

⁷⁵ Celia et al., "Status of CO₂ Storage in Deep Saline Aquifers with Emphasis on Modeling Approaches and Practical Simulations."

⁷⁶ ZHAOWEN LI et al., "CO₂ Sequestration in Depleted Oil and Gas Reservoirs."

⁷⁷ Celia et al., "Status of CO₂ Storage in Deep Saline Aquifers with Emphasis on Modeling Approaches and Practical Simulations."

⁷⁸ National Academies of Sciences, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*.

⁷⁹ Kelemen et al., "An Overview of the Status and Challenges of CO₂ Storage in Minerals and Geological Formations."

⁸⁰ Celia et al., "Status of CO₂ Storage in Deep Saline Aquifers with Emphasis on Modeling Approaches and Practical Simulations."

requirements⁸¹, but there are some non-porous formations that satisfy capacity and injectivity requirements – namely salt caverns⁸².

For sedimentary reservoirs that satisfy capacity and injectivity requirements (i.e. are sufficiently porous and permeable), meeting containment requirements necessitates a non-permeable caprock (also called a reservoir seal) overlying the reservoir⁸³. In general, a caprock is any rock that prevents the flow of a given fluid at a certain temperature, pressure, and chemical environment. Rocks that act as caprocks for supercritical CO₂ include mudstones, shales, evaporites, and tight carbonates⁸⁴. There are some emerging technologies in mineralization that may reduce or eliminate the reliance on caprocks⁸⁵, but injection practices into igneous formations are less mature than in sedimentary formations.

In addition to the fundamental requirements of capacity, injectivity, and containment, another major consideration is depth. A site must be deep enough that CO₂ can be injected as a supercritical fluid and remain supercritical once injected – a depth of 800 m – 1000 m or more.⁸⁶ Beyond these fundamental requirements, screening requirements between each type of geological formation will vary⁸⁷.

Geological media that have identified potential for CCS based on the above criteria include:

- Saline aquifers
- Depleted hydrocarbon reservoirs
- Un-mineable coal seams
- Salt domes/mined caverns
- Organic-rich shales
- Igneous formations suitable for in-situ mineralization

Of the formations that satisfy the above conditions, saline aquifers and depleted hydrocarbon reservoirs have been identified as the most promising and have been proven successful by both pilot projects and large-scale industrial operations. The relative pros and cons of each formation will be discussed.

⁸¹ Celia, “Geological Storage of Captured Carbon Dioxide as a Large-Scale Carbon Mitigation Option.”

⁸² Yang et al., “Feasibility Analysis of Using Abandoned Salt Caverns for Large-Scale Underground Energy Storage in China.”

⁸³ Ismail and Gaganis, “Carbon Capture, Utilization, and Storage in Saline Aquifers.”

⁸⁴ Busch and Kampman, “Migration and Leakage of CO₂ From Deep Geological Storage Sites.”

⁸⁵ Kelemen et al., “An Overview of the Status and Challenges of CO₂ Storage in Minerals and Geological Formations.”

⁸⁶ Celia, “Geological Storage of Captured Carbon Dioxide as a Large-Scale Carbon Mitigation Option.”

⁸⁷ National Academies of Sciences, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*.

6.1.1 Saline Aquifers

An aquifer is a subsurface layer of porous and permeable rock filled with saline water or fresh water⁸⁸. Many properties of saline aquifers make them desirable for use in CCS projects. Unlike the water stored in freshwater aquifers, the brine stored in saline aquifers is not fit for consumption, so they have limited practical use outside of CCS. They are widespread in sedimentary basins across the globe, and thus accessible targets for CCS.⁸⁹ Saline aquifers have largest identified storage capacity relative to other geological media.⁹⁰ Another desirable property of saline aquifers is the variety of mechanisms present that trap the CO₂ underground: in addition to trapping CO₂ with a caprock and in pore spaces via capillary forces, aquifers have the potential to dissolve CO₂ into the reservoir brine and eventually mineralize it into a stable carbonate form. These trapping mechanisms will be discussed in further detail in the next section.

The drawback of using saline aquifers is the high cost due to lack of existing infrastructure and intensive screening requirements.⁹¹ Furthermore, saline aquifers and other porous reservoirs are very reliant on an uncompromised caprock to keep the CO₂ trapped underground. Thus, caprock integrity is a major concern for storage in saline aquifers (and other porous reservoirs). Furthermore, injection operations in saline aquifers require more stringent pressure management requirements than in un-saturated porous reservoirs. Pore space in saline aquifers is occupied by brine and displacing that brine with CO₂ can cause rapid increases in pressure if not managed properly.⁹²

CCS in saline aquifers is one of the most mature CCS technologies, with many pilot projects and industrial-scale projects having operated for years already. The most recognizable projects include Sleipner, Snohvit, In Salah, Frio, and Ketzin.⁹³

6.1.2 Depleted Hydrocarbon Reservoirs and CO₂-EOR+

There are three phases of production during extraction from an oil or gas well: (i) primary production, when oil flows due to reservoir pressure, (ii) secondary production, when an immiscible fluid is injected to increase pressure and flow, and (iii) tertiary production, when CO₂ or another fluid is used for enhanced oil recovery (EOR). During EOR, CO₂ moves through the reservoir, displacing oil residue that is trapped in rock pores and mobilizing it. In the process, CO₂ gets residually trapped. With each recovery cycle, more CO₂ is retained. The total volume of storage depends on the site and other operational factors.

⁸⁸ Al-Shafi et al., "A Review on Underground Gas Storage Systems."

⁸⁹ Newell and Ilgen, "Overview of Geological Carbon Storage (GCS)."

⁹⁰ Rasool, Ahmad, and Ayoub, "Selecting Geological Formations for CO₂ Storage."

⁹¹ Ismail and Gaganis, "Carbon Capture, Utilization, and Storage in Saline Aquifers."

⁹² Mim et al., "Minireview on CO₂ Storage in Deep Saline Aquifers."

⁹³ Mim et al.

Once oil and gas wells become unproductive (and/or after EOR operations finish), they have the potential to be used as GCS reservoirs. Since hydrocarbon wells are porous and permeable, the storage mechanisms employed are similar to those in saline aquifers⁹⁴. Although depleted oil wells have significantly less storage capacity than saline aquifers, they are desirable in other ways; known site data and existing critical infrastructure make the injection process easier.⁹⁵ Key factors such as capacity and caprock seal quality are already known⁹⁶. Pipelines, injection wells, and production wells already exist on site. Due to the oil and gas industry's decades-long experience performing EOR, injection methods are familiar and mature. Furthermore, since pore space is only occupied by residual hydrocarbons and injection fluids, and not saturated with brine as in saline aquifers, pressure management is not as demanding. However, this comes at the expense of certain trapping mechanisms; in the absence of aquifer brine, mineralization may occur significantly less or not at all. Storage in depleted reservoirs is thus much more dependent on caprock integrity and capillary forces to keep the CO₂ trapped underground. Trapping mechanisms will be discussed in further depth in the following section.

When discussing GCS in depleted hydrocarbon reservoirs, enhanced oil recovery must be discussed. The process of injecting CO₂ into oil and gas wells is a well-established technology in the hydrocarbon industry, and one that has been practiced for decades. Enhanced oil recovery (EOR) is the process of injecting a fluid into non-productive wells to increase pressure and mobilize more oil and gas. When performed with supercritical CO₂, this is called CO₂-EOR. It must be stressed that CO₂-EOR is not by intent or design a form of GCS, but some CO₂ is sequestered in the well formation during each injection cycle. CO₂-EOR+ is a modified EOR procedure aimed at reducing CO₂ usage or increasing CO₂ sequestration during injection. There are three notable models of CO₂-EOR+:

- Conventional EOR+
- Advanced EOR+
- Maximum Storage EOR+

Conventional EOR+ is very similar to conventional CO₂-EOR, but optimized to reduce CO₂ usage. Advanced EOR+ is optimized for oil recovery. Maximum storage EOR+ is optimized for sequestration. On average, one barrel of oil releases around 500 kg of CO₂ over its lifecycle (100 kg during production, processing, and transport, and 400 kg when combusted)⁹⁷. If injected carbon that is not sequestered on its first pass is separated and re-injected to form a closed-loop EOR system, EOR+ can store between 300 kg and 600 kg of CO₂ per barrel of oil produced.⁹⁸ The range in kg is a result of the variation in sequestration between conventional, advanced, and

⁹⁴ Al-Shafi et al., "A Review on Underground Gas Storage Systems."

⁹⁵ Heidarabad and Shin, "Carbon Capture and Storage in Depleted Oil and Gas Reservoirs."

⁹⁶ Raza et al., "A Screening Criterion for Selection of Suitable CO₂ Storage Sites."

⁹⁷ "Can CO₂-EOR Really Provide Carbon-Negative Oil?"

⁹⁸ "Can CO₂-EOR Really Provide Carbon-Negative Oil?"

maximum storage EOR+. Thus, EOR+ presents the possibility for carbon-neutral or carbon-negative oil.

6.1.3 Un-Mineable Coal Seams

Coal seams that are too difficult or un-economical to extract have the potential to be used for GCS. Coal seams are porous and may contain methane. If methane is present, it gets displaced by injected CO₂ and can be produced as a profitable byproduct. This is called enhanced coal bed methane (ECBM) recovery.

The practicality of storage in coal seams is questionable; the permeability of coal decreases with depth and as CO₂ is injected, such that injection threatens the sealing layer. Technical challenges have prevented large scale application and testing⁹⁹. It is currently not considered reliable and has been abandoned in practice¹⁰⁰

6.1.4 Salt Caverns

Salt caverns are artificially formed using solution mining, a process where freshwater is injected into an existing salt bed or dome, dissolving a cavern out of the salt bed.¹⁰¹ Salt caverns have desirable self-sealing properties. The storage duration in salt caverns depends on the depth of the cavern, and ranges from hundreds of years to thousands of years.¹⁰² GCS in salt caverns is not a mature technology – researchers in China have verified feasibility and capacity worth investigating, but pilot projects are needed to develop the method further.¹⁰³

6.1.5 Organic-Rich Shales

Shales, a type of non-permeable rock, are typically used as caprocks in GCS, not reservoirs. However, organic-rich shales that have been subject to hydraulic fracturing (fracking) have usage potential for GCS¹⁰⁴. Shale formations are abundant and deep, and fracking operations can result in a fracture network of approximately 35,000 cubic meters per well. CO₂ stored in shale formations can be trapped in fractures and sorbed onto organic matter and clays¹⁰⁵. This is not a well-developed GCS process; major limitations include difficulty estimating capacity and a lack of empirical data.

⁹⁹ National Academies of Sciences, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*.

¹⁰⁰ Celia et al., “Status of CO₂ Storage in Deep Saline Aquifers with Emphasis on Modeling Approaches and Practical Simulations.” Celia et al.

¹⁰¹ Al-Shafi et al., “A Review on Underground Gas Storage Systems.”

¹⁰² Yang et al., “Feasibility Analysis of Using Abandoned Salt Caverns for Large-Scale Underground Energy Storage in China.”

¹⁰³ Zhang et al., “Large-Scale CO₂ Disposal/Storage in Bedded Rock Salt Caverns of China.”

¹⁰⁴ Sharma et al., “Geochemical Controls on CO₂ Interactions with Deep Subsurface Shales.”

¹⁰⁵ Sharma et al.

6.1.6 In-Situ Mineralization in Igneous Formations

Mineralization in igneous formations is distinct from GCS operations in sedimentary basins. Although basalt is highly porous and permeable, its most desirable property is its reactivity with CO₂, which results in the formation of stable carbonates after CO₂ is injected.¹⁰⁶ Mineralization projects do not rely on reservoir seals so much as rapid mineralization and dissolution of CO₂ in the basalt formation. Although mineralization technologies have the potential to be very secure, they are still in development. There are few pilot projects – namely Wallula (USA) and CarbFix (Iceland)¹⁰⁷. More industrial scale studies and pilot projects will be required to determine the large-scale viability of CO₂ mineralization.

6.2 Immobilization and Trapping

This section will discuss the various mechanisms that trap CO₂ in underground reservoirs and immobilize it over time.

6.2.1 Trapping Mechanisms

Once CO₂ is injected into a geological formation, multiple trapping mechanisms begin to act upon it. Trapping mechanisms vary depending on the type of geological formation, and within a formation will vary in rate and permanence. These mechanisms can be broadly categorized into physical and chemical trapping mechanisms. Physical trapping is typically more rapid but less secure than chemical trapping. Physical trapping mechanisms include structural/stratigraphic trapping and residual trapping. Chemical trapping mechanisms include solubility trapping, mineralization, and adsorption.

Since GCS in saline aquifers is the most viable for large-scale implementation, trapping mechanisms will be discussed in reference to saline aquifers (porous media, brine, caprock, etc.) with specifications/comparisons made when necessary.

In the context of trapping and immobilization, the term “security” will be used to describe the risk of reversal in reference to a specific trapping mechanism.

Structural/stratigraphic (also called hydrodynamic or buoyancy) trapping occurs when CO₂ is trapped within stable geological structures. Structural traps include anticline and fault traps whereas stratigraphic traps are formed due to changes in lithology (i.e. rock type). The non-permeable caprock layer over a permeable reservoir forms a stratigraphic trap.

Structural/stratigraphic traps are the least secure of all trapping mechanisms since they are the easiest to reverse. A caprock layer with no significant fractures has the potential to store CO₂

¹⁰⁶ Raza et al., “Carbon Mineralization and Geological Storage of CO₂ in Basalt.”

¹⁰⁷ Kelemen et al., “An Overview of the Status and Challenges of CO₂ Storage in Minerals and Geological Formations.”

indefinitely, but fractures or other breaches in the caprock caused by injection or seismic activity will lead to CO₂ leakage.

Residual/capillary trapping is driven by capillary forces and wetting phenomena. As injected CO₂ moves through the (typically) porous rock in a reservoir, high capillary pressures will immobilize the CO₂. The level of residual trapping depends on the formation and what media occupies the pore space before injection. For example, the pore space in saline aquifers is filled by wetting-phase brine, and these brine particles increase the capillary pressure on non-wetting phase CO₂ as it moves through the pore system. Higher capillary pressure results in more residual trapping and thus security but is also associated with pressure build-up and lower injectivity. Residual trapping is more secure than structural trapping and requires reverse engineering to undo. For example, consider EOR operations whose primary goal is to release residually trapped oil and gas from hydrocarbon reservoirs.

Solubility trapping occurs when the injected CO₂ dissolves into the formation fluid (brine, water, or hydrocarbons). It is more secure than both structural and residual trapping because CO₂ is unlikely to abandon its host solution unless a significant drop in pressure occurs. Solubility trapping is associated with saline aquifers, as the availability of reservoir brine leads to a significant solubility contribution over time. Although reservoir fluid may also be present in depleted reservoirs, less dissolution is predicted to occur.¹⁰⁸

Mineralization occurs when CO₂ reacts with minerals in the formation to form stable carbonates. Mineralization occurs over thousands of years in saline aquifers, but in reactive formations like basalts can occur in as little as decades. Mineralization is the most secure trapping mechanism, and once CO₂ is mineralized it can be considered permanently sequestered. Mineralization is also associated with saline aquifers, as the geochemical interactions between CO₂ and saline reservoir brine lead to the eventual precipitation of carbonates in the reservoir.

Adsorption occurs in GCS formations such as depleted wells and coal seams that contain organic materials. The CO₂ adsorbs to the organic materials and is trapped. Adsorption is associated with depleted oil wells, un-mineable coal seams, and organic-rich shales.

¹⁰⁸ Liu et al., “Pore-Scale Phenomena in Carbon Geological Storage (Saline Aquifers—Mineralization—Depleted Oil Reservoirs).”

6.2.2 Timescales

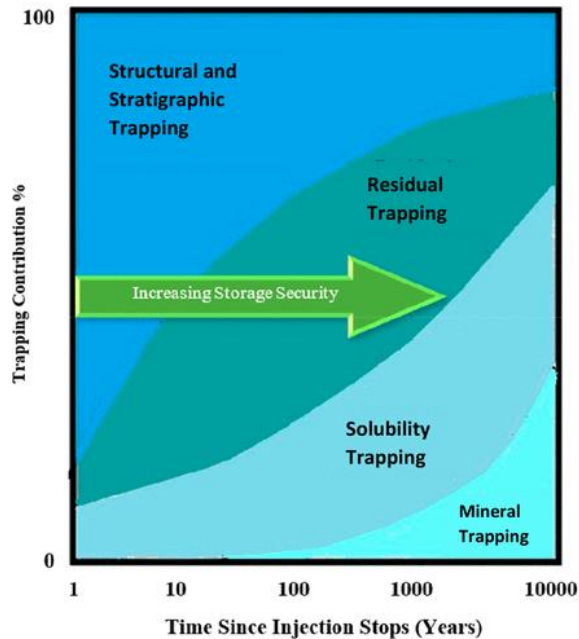


Figure 1: Contributions of Various Trapping Mechanisms in Saline Aquifers¹⁰⁹.

Figure 1 represents the contributions of different trapping mechanisms in a saline aquifer over time.¹¹⁰ Containment relies heavily on stratigraphic trapping by the caprock during the injection period, which is typically 30-40 years. For the first 10 years of injection, well over half of the injected carbon is contained solely by the caprock. As such, the risk of leakage is highest during the injection period, when improper pressure management can result in caprock fractures.

As time goes on, the contribution of other trapping mechanisms increases and the risk of significant leakage decreases. The exact contributions of each trapping mechanism will depend on the porosity, pressure, temperature, and salinity (if applicable) of a site.

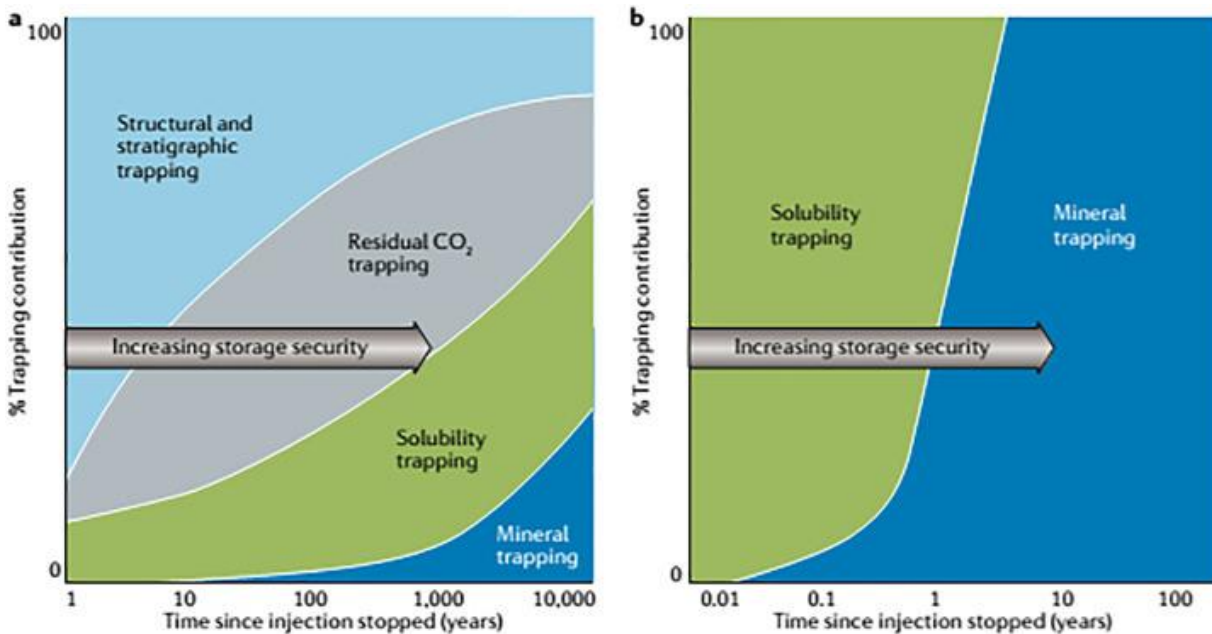


Figure 2: Comparison of Trapping Mechanism Contributions in Saline Aquifers (Left) and Basalt Formations (Right)

¹⁰⁹ Ismail and Gaganis, “Carbon Capture, Utilization, and Storage in Saline Aquifers.”

¹¹⁰ Mim et al., “Minireview on CO₂ Storage in Deep Saline Aquifers.”

Figure 2 demonstrates the difference in trapping mechanism contribution over time between a conventional sedimentary site and an igneous formation (such as basalt).¹¹¹ As illustrated in the figure, GCS in sedimentary sites relies heavily on proper site characterization and pressure management to preserve caprock integrity. GCS in volcanic formations, on the other hand, is designed to become permanent almost immediately in a geological timescale.

6.3 Leakage

This section will discuss the mechanisms that lead to leakage of CO₂ after injection.

6.3.1 Leakage Pathways

The most significant concern associated with GCS is of CO₂ leakage. If stored CO₂ can permeate through the reservoir seal, it will continue to migrate upwards through overlying units. Leakage pathways fall into one of three categories: (i) caprock permeability, (ii) wellbores, and (iii) faults and fractures.

6.3.1.1 Caprock Permeability

Leakage via caprock permeability occurs when the sealing unit of a GCS reservoir has non-zero permeability and injection pressure is too high. This results in CO₂ or, more likely, formation fluid being pushed through the caprock layer. Leakage through the caprock layer can be avoided by proper site selection and pressure management. Leakage via caprock permeability is manageable, and only poses a significant threat if there are localized zones with high permeability, as this points to fractures or faults in the caprock layer¹¹². If leakage of brine through the caprock does occur, it will likely have a net positive outcome by relieving reservoir pressure.

6.3.1.2 Wells/Wellbores

Wells and wellbores, also called engineered pathways, pose a significant logistical threat to GCS operations. Every well involved in a GCS operation creates some risk: pre-existing wells (abandoned or orphaned), injection wells, and long-term monitoring wells are all leakage pathways until they are plugged. Wells plugged before GCS operations likely need to be reinforced, as they are not designed to withstand a CO₂-rich environment. For example, the dissolution of CO₂ in brine lowers the pH of the brine, making it corrosive to steel and cement, which are the materials used to plug wells. If a well is not properly plugged, CO₂ can migrate through interfaces between the cement and steel casing, the cement matrix, fractures in the cement, holes within the casing, or interfaces between cement and rock.¹¹³

¹¹¹ Raza et al., “Carbon Mineralization and Geological Storage of CO₂ in Basalt.”

¹¹² Celia et al., “Status of CO₂ Storage in Deep Saline Aquifers with Emphasis on Modeling Approaches and Practical Simulations.”

¹¹³ Busch and Kampman, “Migration and Leakage of CO₂ From Deep Geological Storage Sites.”

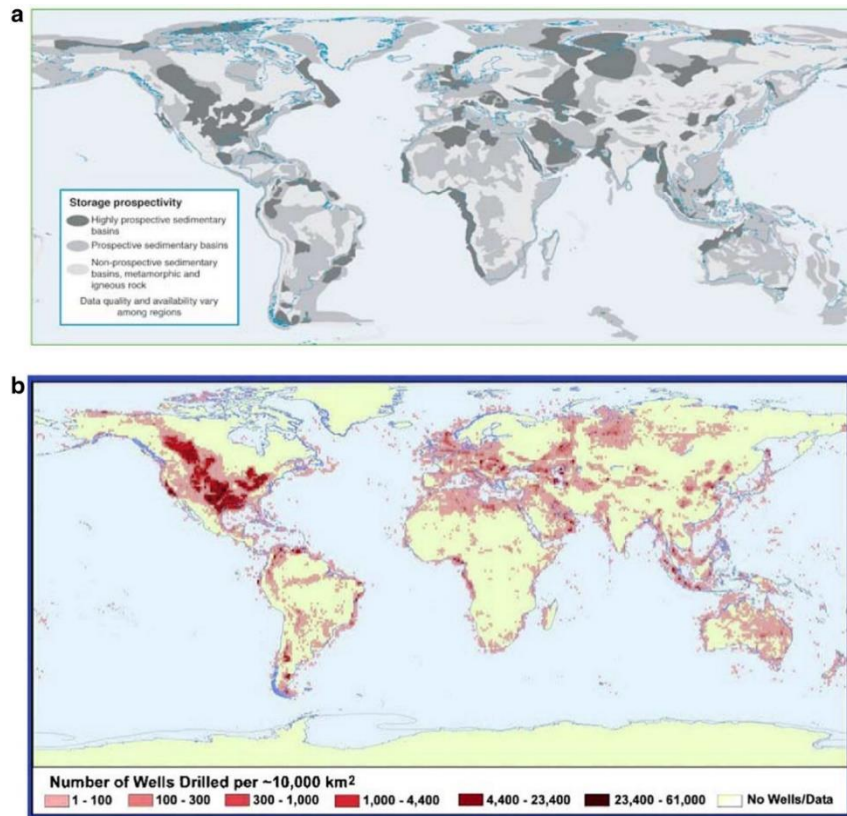


Figure 3: Top: Locations of sedimentary basins suitable for GCS. Bottom: Density of wellbores.

Figure 3 demonstrates the locations of sedimentary basins suitable for GCS across the globe in comparison with the density of wells and wellbores drilled.¹¹⁴ There are over 500,000 wells in Western Canada alone.¹¹⁵ Well remediation will be discussed further in the next section.

6.3.1.3 Fractures/Faults

If caprock integrity is not properly assessed before injection, CO₂ can leak through fractures and/or faults in the caprock. Leakage through fractures and faults can be avoided via proper site characterization and screening.

6.4 Well Remediation and Site Preparation

When an oil or gas well is depleted, often it is abandoned or orphaned. The United States Environmental Protection Agency (EPA) estimates that on average, each unplugged inactive oil and gas well emits 0.13 metric tons of methane annually.¹¹⁶ With roughly 466,000 abandoned wells in Alberta alone, this would equate to over 40,000 metric tons of methane being released

¹¹⁴ Celia et al., “Status of CO₂ Storage in Deep Saline Aquifers with Emphasis on Modeling Approaches and Practical Simulations.”

¹¹⁵ “Orphan Well Association Annual Report 2022/23.”

¹¹⁶ CGEP, “Green Stimulus for Oil and Gas Workers.”

annually.¹¹⁷ At this point in the well’s life cycle, the next step is the remediation of the site. As of 2020, there were between 60,000 – 100,000 plugged or reclaimed wells in Alberta, shown in Figure 4.¹¹⁸

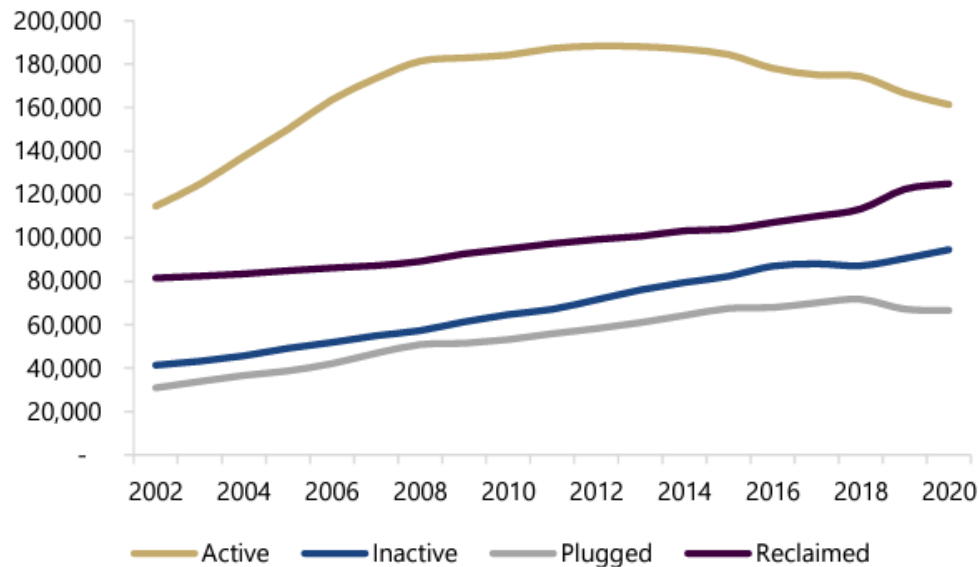


Figure 4: The number of wells, categorized into 4 categories: active, inactive, plugged and reclaimed in Alberta between 2002 and 2020.¹¹⁹

The process of remediating wells includes removing the contaminants and restoring a well’s geological integrity. Essentially, any health and environmental hazards associated with a well will be mitigated. Remediation includes the plugging and mitigation of hazards. Regarding characterizing a well for CO₂ injection, remediation will only include mitigating contaminants at the site. The site will not need to be plugged in as the bore hole will be used as an injection zone.

- Abandoned well: a well that is depleted and no longer active (producing oil or gas).
- Orphaned well: When there is no known, financially viable operator capable of cleaning and closing a well.¹²⁰
- Remediation: contaminants at the site are managed and removed.¹²¹
- Reclamation: the land the site is on is returned to its former, pre-development state.¹²²

Cost and time estimates to remediate wells include the plugging and contaminant remediation at the site. Therefore, the cost to remediate for carbon sequestration will be less than researched

¹¹⁷ “How Are Wells Abandoned?”

¹¹⁸ Office of the Parliamentary Budget Officer, “Estimated Cost of Cleaning Canada’s Orphan Oil and Gas Wells.”

¹¹⁹ Office of the Parliamentary Budget Officer.

¹²⁰ Office of the Parliamentary Budget Officer.

¹²¹ Office of the Parliamentary Budget Officer.

¹²² Office of the Parliamentary Budget Officer.

values. Table 4 shows a comparison of two sources that have estimated the cost to remediate an abandoned oil or gas well.

However, as explained by Raimi et al., the cost and time required to remediate is dependent on many factors¹²³, some of these are explained in the following list:

Factors Effecting the Efficiency of Remediation¹²⁴

- Well depth: deeper wells have the potential to require more mitigation as there are more opportunities for fracked caprock and subsequent leakage.¹²⁵
- Well age: well integrity degrades over time – more potential for contamination via leakage.¹²⁶
- Site topography: sites in hilly terrain will be more costly due to erosion concerns and costs of transporting materials.¹²⁷
- Gas or oil well: gas wells may be more expensive because gas naturally flows to the surface, while a depleted oil well loses most of its natural pressure.¹²⁸ However, oil wells may have surface spills that will need to be remediated.

Table 4: Cost estimates for individual well remediation.

Source	Remediation (with plugging) (USD)	Time to Remediate
Review by Raimi et al. (United States)	56,000 ¹²⁹	1 day – several weeks ¹³⁰
ALDP (Canada)	79,000 – 143,000 ¹³¹	

In a study by Alberta’s energy regulator in 2024, the estimate to clean up the hundreds of thousands of wells would be \$33.3 billion.¹³² This estimate is derived from the cost to remediate individuals wells in different areas of the province.¹³³ However, it is discussed in the media that

¹²³ Raimi et al., “Decommissioning Orphaned and Abandoned Oil and Gas Wells.”

¹²⁴ Raimi et al.

¹²⁵ Raimi et al.

¹²⁶ Kiran et al., “Identification and Evaluation of Well Integrity and Causes of Failure of Well Integrity Barriers (A Review).”

¹²⁷ Raimi et al., “Decommissioning Orphaned and Abandoned Oil and Gas Wells.”

¹²⁸ Raimi et al.

¹²⁹ Raimi et al.

¹³⁰ Raimi et al.

¹³¹ Alberta Liabilities Disclosure Project, “The Big Clean-Up.”

¹³² “Internal Documents Suggest Alberta Energy Regulator Underestimated Oil Well Liability.”

¹³³ “Internal Documents Suggest Alberta Energy Regulator Underestimated Oil Well Liability.”

these estimates may be too low, due to the system of estimation that underestimates the environmental liabilities regarding the oil wells.¹³⁴

6.5 Reservoir Characterization and Site Screening

Once a well site has been remediated, the site can be evaluated as a potential site for carbon sequestration – where existing well boreholes are used as an injection site. An injection well will inject compressed carbon through an injection zone into a confining zone – whether that is a depleted oil reservoir or saline aquifer.¹³⁵ Figure 5 shows the anatomy of an injection well. Reusing abandoned oil and gas wells is an opportunity to reduce the cost and labour of building new infrastructure for an injection well.

To evaluate the use of abandoned oil and gas wells as injection wells for geological sequestration, a particular set of standards that measure their viability is proposed by the United States Environmental Protection Agency (USEPA), outlined in Figure 6. This process is that of determining the viability of what the USEPA calls a Class VI Well, which are wells that are not experimental in nature that are used for geological sequestration of carbon dioxide beneath the lowermost formation containing an underwater source of drinking water.¹³⁶ These processes of determining viability are applicable to any oil well site that has been identified to be used for carbon storage.¹³⁷

A summary of the information required to determine a well’s suitability to be used an injection site is shown below.¹³⁸

- Maps and cross sections of the area of review
- Location, orientation, and properties of known or suspected faults (fractures in caprock) that transect the confining zone.

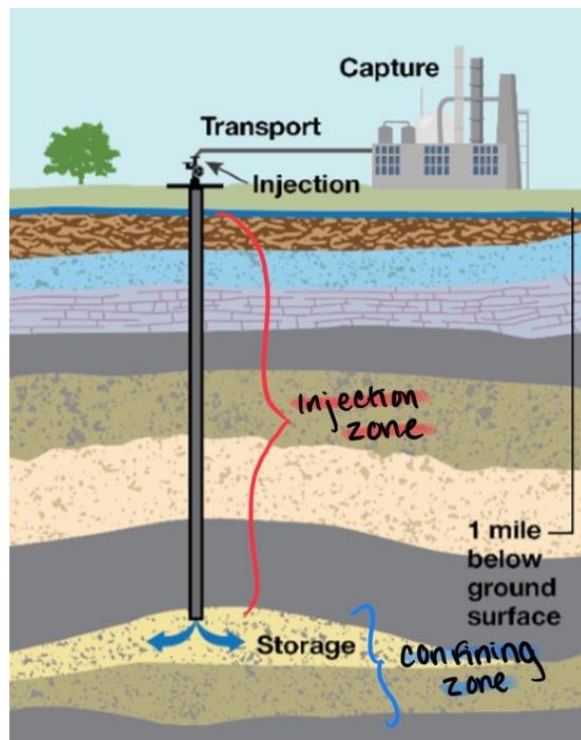


Figure 5: Image outlining injection and confining zones.¹⁰⁶

¹³⁴ Weber, “Alberta Regulator’s \$33B Well Cleanup Liability Estimate Called Too Low.”

¹³⁵ “Geologic Sequestration of Carbon Dioxide - Underground Injection Control (UIC) Program Class VI Well Site Characterization Guidance.”

¹³⁶ “Class VI Well Site Characterization Guidance.”

¹³⁷ Ismail and Gaganis, “Carbon Capture, Utilization, and Storage in Saline Aquifers.” Ismail and Gaganis.

¹³⁸ “Geologic Sequestration of Carbon Dioxide - Underground Injection Control (UIC) Program Class VI Well Site Characterization Guidance.”

- Data of the depth, areal extent, thickness, mineralogy, porosity, permeability and capillary pressure of injection and confining zones
- Geomechanical information on fractures, stress, ductility, rock strength, and in situ fluid pressures within the confining zone(s).
- Seismic history of the area, with presence and depths of seismic sources and determination that seismicity will not interfere with containment.

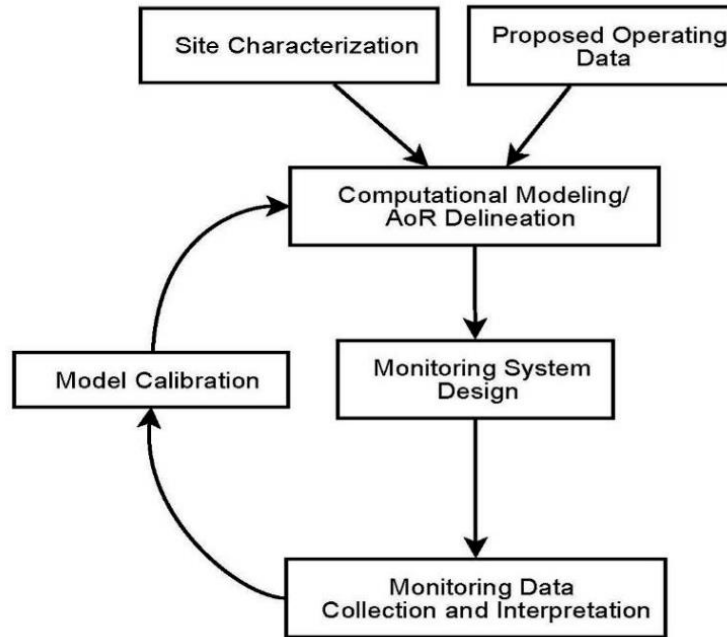


Figure 6: Flow chart outlining the process of determining the suitability of a site to be repurposed as an injection well.¹⁰⁷

Potential hurdles with site characterization:¹³⁹

1. Lack of data
2. Subsurface parameter uncertainty
3. Complex subsurface geology

Since many wells that can be remediated and repurposed for injection are abandoned or orphaned, there is often the problem of a lack of data. This may make it infeasible to be used as the collection of data will delay the processing time and increase the number of resources needed.

6.6 Injection Process

The process of injecting carbon dioxide into any storage option requires it to be compressed and cooled to bring the CO₂ into a supercritical state. In this state, the carbon dioxide will have properties of both liquid and gas, with a volume that will expand to fill a container and the

¹³⁹ Ismail and Gaganis, "Carbon Capture, Utilization, and Storage in Saline Aquifers." Ismail and Gaganis.

density of a liquid. The supercritical point of carbon dioxide is 31.1°C and 7380 kPa (~1070 psi).¹⁴⁰

To proceed in the injection of carbon dioxide, the accurate characterization of the storage reservoir and site of interest is required.¹⁴¹ When potential sites are identified, they are screened based on geologic and environmental data as described previously.

An injection well will pump the supercritical carbon dioxide into a chosen storage reservoir. Regardless of the type of storage, it must be at least one mile (~1.4 kilometers) deep from the surface to have appropriate pressure. Injection zones are geologic formations or a part of a formation that is of sufficient areal extent, thickness, porosity, and permeability to receive carbon dioxide through a well or wells associated with a geological sequestration project¹⁴². Confining zones are geologic formations or part of a formation that is stratigraphically overlying and underlying the injection zone that acts as a barrier to fluid movement.¹⁴³ Often, injection wells are repurposed oil and gas wells that have been depleted of natural gas. This is a cost-effective alternative to drilling new holes for injection into reservoirs.

6.6.1 Pressure Management

The injection of CO₂ into a geological reservoir increases the reservoir pressure. In sedimentary reservoirs that rely on a caprock for containment, if reservoir pressure exceeds caprock fracture pressure, injection can fracture the caprock. Pressure management is the control of injection pressure, injection rate, and injection site to keep reservoir pressure below required thresholds. In saline aquifers, brine can be extracted to reduce reservoir pressure.¹⁴⁴

6.7 Monitoring Techniques

It is essential to monitor the leakage of Carbon Capture and Storage, especially when assessing its environmental impact. Recent advancements in technology have enhanced the accuracy and efficiency of detecting carbon leakage from storage sites. These methods include (i) radiocarbon analysis, (ii) colorimetric CO₂ sensors, and (iii) remote sensing approaches. Additional methods do exist, and there is great potential for future development in the field of monitoring. However, these methods offer unique advantages regarding sensitivity, spatial and temporal coverage, and cost-effectiveness. By differentiating between CO₂ from natural and fossil fuel sources, radiocarbon analysis offers a trustworthy indicator of leakage. Colorimetric CO₂ sensors, on the other hand, provide a portable, affordable option for on-the-ground monitoring combined with

¹⁴⁰ Budisa and Schulze-Makuch, "Supercritical Carbon Dioxide and Its Potential as a Life-Sustaining Solvent in a Planetary Environment." Budisa and Schulze-Makuch.

¹⁴¹ Ismail and Gaganis, "Carbon Capture, Utilization, and Storage in Saline Aquifers." Ismail and Gaganis.

¹⁴² "Geologic Sequestration of Carbon Dioxide - Underground Injection Control (UIC) Program Class VI Well Site Characterization Guidance." [CSL STYLE ERROR: reference with no printed form.].

¹⁴³ *ibid.*

¹⁴⁴ Raza et al., "A Screening Criterion for Selection of Suitable CO₂ Storage Sites."

the ease of remote data access. By utilizing the most recent advancements in satellite and aerial technology, remote sensing provides a non-contact, economical method of identifying changes linked to CCS leakage by enabling thorough vegetation monitoring over large areas. Combined, these technologies offer a multifaceted approach to monitoring, emphasizing the importance of choosing the proper technique depending on the demands of a particular project and environmental factors. Although these methods can be used at any stage of the CCS lifetime, they are especially important for the long-term monitoring of facilities that store carbon.

6.8 Radiocarbon Analysis

Radiocarbon measurements can detect carbon dioxide leaks from stored carbon facilities into the atmosphere. Their ability to clearly distinguish between natural CO₂ sources that contain ambient radiocarbon levels and fossil-derived CO₂, which is devoid of ¹⁴C radiocarbon, makes them unique.¹⁴⁵ This capability allows for detecting leaks that negate CCS's climate mitigation efforts or pose health risks and aids in monitoring CCS's effectiveness and environmental safety.

In the study by Turnbull et al. on “Atmospheric monitoring of carbon capture and storage leakage using radiocarbon,” They offer an essential process for utilizing radiocarbon (¹⁴C) readings to locate CO₂ leakage from Carbon Capture and Storage (CCS). This strategy uses the unique isotopic difference between natural CO₂ sources, which have ambient radiocarbon levels, and fossil-derived CO₂, which does not.¹⁴⁶ This difference provides a unique flag for CCS leakage identification. The method's 1 ppm fossil-derived CO₂ detection threshold aligns with existing atmospheric detection techniques' sensitivity for detecting CCS leaks, demonstrating its effectiveness in differentiating recently added fossil-derived CO₂ in the atmosphere.¹⁴⁷

Furthermore, the study illustrates the method's ability to identify a 1000-ton-per-year CCS leak within a few hundred meters of the source through model simulations and field experiments. A case study in Taranaki, New Zealand is included, where nighttime detection proved to be more successful due to atmospheric conditions.¹⁴⁸ The study highlights the feasibility of the approach despite the possibility of false positives from other nearby fossil CO₂ sources. It highlights the adaptability of sample materials, from short-lived grass leaves to cellulose in tree rings, enabling dense spatial sampling at low cost.¹⁴⁹ By guaranteeing carbon sequestration procedures' integrity and environmental safety, the analysis highlights the radiocarbon method's potential as a

¹⁴⁵ Turnbull et al., “Atmospheric Monitoring of Carbon Capture and Storage Leakage Using Radiocarbon - ScienceDirect.”

¹⁴⁶ Turnbull et al.

¹⁴⁷ Turnbull et al.

¹⁴⁸ Turnbull et al.

¹⁴⁹ Turnbull et al.

dependable and affordable tool for monitoring CCS operations, assisting efforts to mitigate climate change.

6.9 Colorimetric CO₂ Sensors

In the article “Highly Efficient Colorimetric CO₂ Sensors for Monitoring CO₂ Leakage from Carbon Capture and Storage Sites” by Ko, Lee and Chung (2020), they present developments of a low-cost, portable colorimetric CO₂ sensor to monitor CO₂ leakage from CCS sites.¹⁵⁰ The sensor provides a quick and effective fix for CCS monitoring problems by measuring soil CO₂ concentrations using a pH indicator enclosed in a gas-permeable membrane. It can also detect low levels of CO₂ within minutes and can be used for remote monitoring on your smartphone.¹⁵¹ This is a significant improvement compared to traditional CO₂ sensors, which are frequently costly and require specialist personnel for maintenance. The sensor's excellent sensitivity and efficiency were proved in laboratory experiments, wherein CO₂ concentrations ranging from 0.1% to 30% were detected.¹⁵² Field investigations highlighted its practical application in real-world scenarios that further confirmed its effectiveness in detecting surficial CO₂ leakage patterns at natural and artificial CO₂ leaking locations.¹⁵³

The accuracy of CO₂ measurements may be impacted by several possible areas for development, such as the sensor's performance under different ambient light situations. Furthermore, additional research is necessary to guarantee the sensor's durability for long-term field applications due to its resilience to changing weather conditions.¹⁵⁴ Future research to improve these aspects of the sensor will likely strengthen its potential as an affordable means of guaranteeing public and environmental safety by expanding its usefulness for thoroughly monitoring CO₂ leakage from CCS sites.

6.10 Remote Sensing

Active and passive remote sensing approaches provide CCS projects with economical and effective monitoring options. While passive remote sensing looks for naturally occurring radiation the target emits or reflects, active remote sensing entails producing radiation and monitoring the reaction.¹⁵⁵ Carbon-observing satellites, grating spectrometers, airborne

¹⁵⁰ Ko, Lee, and Chung, “Highly Efficient Colorimetric CO₂ Sensors for Monitoring CO₂ Leakage from Carbon Capture and Storage Sites - ScienceDirect.”

¹⁵¹ Ko, Lee, and Chung.

¹⁵² Ko, Lee, and Chung.

¹⁵³ Ko, Lee, and Chung.

¹⁵⁴ Ko, Lee, and Chung.

¹⁵⁵ Zhang et al., “CO₂ Capture and Storage Monitoring Based on Remote Sensing Techniques: A Review - ScienceDirect.”

spectroscopy, and Open-path Fourier-transform infrared spectroscopy make monitoring CO₂ concentrations and surface deformation possible.

6.10.1 Surface Deformation Monitoring

Monitoring surface deformation is essential for determining how CO₂ injection will affect reservoirs and the surrounding environment. Methods like LiDAR modelling, UAV photogrammetry, and interferometric synthetic aperture radar (InSAR) can help find potential leakage spots.¹⁵⁶ These offer comprehensive insights into ground movement and deformation patterns.

6.10.2 Ecological Environment Monitoring

Conducting ecological environment monitoring is imperative for identifying CO₂ leaks and evaluating their effects on neighboring ecosystems and vegetation. Vegetation monitoring, thermal anomaly detection, soil composition analysis, and biological monitoring identify changes suggestive of CO₂ leakage.¹⁵⁷ These methods inform emergency response plans and provide early warnings.¹⁵⁸

6.10.3 Potential Impacts of Large-Scale CCS Operations

In this section, we examine the effects associated with large-scale CCS operations. The potential for leakage to exacerbate global warming and precipitate adverse health outcomes due to heightened air pollution is explored. It also explores the more indirect effects on human health. This examination showcases the difficulties of broad use of CCS technologies.

6.10.3.1 Exacerbation of Global Warming

Carbon Capture and Storage leakage can contribute to climate change by potentially negating the initial environmental benefits of capturing and storing CO₂ emissions. Over one thousand years, even leakage rates as low as 0.01% to 0.1% per year could result in up to 25GtCO₂ emissions throughout the 21st century, as shown in Figure 7 below.¹⁵⁹

¹⁵⁶ Zhang et al.

¹⁵⁷ Zhang et al.

¹⁵⁸ Zhang et al.

¹⁵⁹ Vinca, Emmerling, and Tavoni, “Bearing the Cost of Stored Carbon Leakage.”

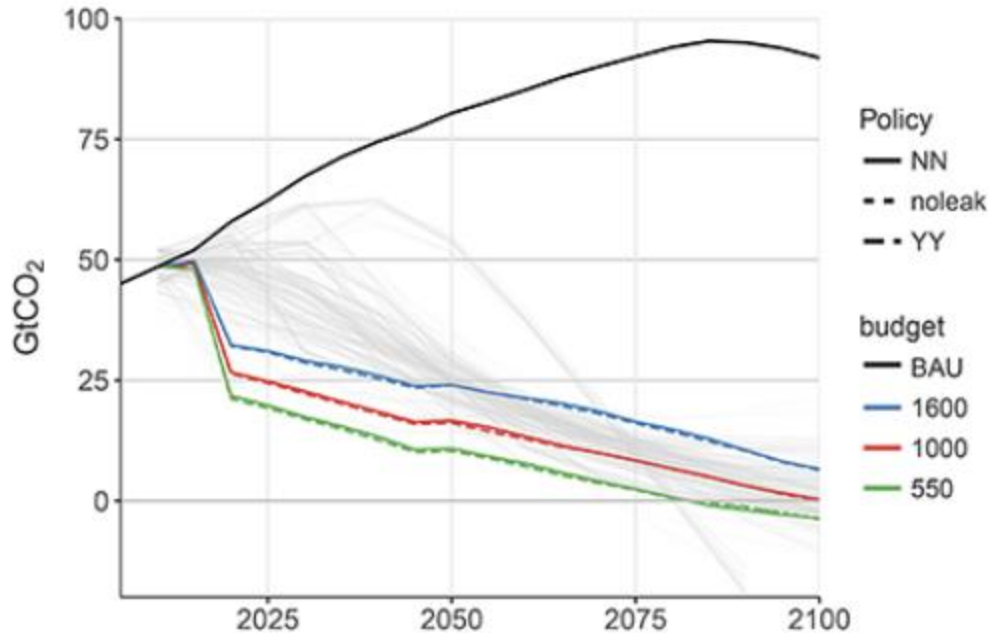


Figure 7: Global greenhouse gas emissions (GtCO₂eq) across scenarios. For targets different from BAU, leakage is set to 0 or 0.1%/year. In gray, the scenarios from the AR5 Scenario Database are plotted in line with 2°C.¹⁶⁰

6.10.3.2 Health Impacts of Air Pollution

Particulate matter (PM) and nitrogen oxide (NO_x) emissions are expected to increase directly to the additional fuel used.¹⁶¹ If more steps are taken to reduce emissions, this growth might be lessened.¹⁶² Particulate matter, especially PM_{2.5}, can cause respiratory and cardiovascular conditions, exacerbate asthma attacks, and even cause early death by penetrating deeply into the lungs and into the bloodstream.¹⁶³ Nitrogen oxide emissions contribute to the creation of ground-level ozone, a dangerous air pollutant that worsens respiratory conditions, impairs lung function and may increase respiratory-related hospital admissions and ER visits.¹⁶⁴

According to projections, the degradation of amine-based solvents used in carbon capture and storage (CCS) technologies' CO₂ capture process may cause ammonia (NH₃) emissions to increase, possibly triple.¹⁶⁵ An increase in ammonia can indirectly affect human health. Ammonia

¹⁶⁰ Vinca, Emmerling, and Tavoni.

¹⁶¹ "Carbon Capture and Storage Could Also Impact Air Pollution — European Environment Agency."

¹⁶² "Sulfur Dioxide | NIOSH | CDC."

¹⁶³ Xing et al., "The Impact of PM_{2.5} on the Human Respiratory System - PubMed."

¹⁶⁴ "Ground-Level Ozone Basics | US EPA."

¹⁶⁵ Lovarelli et al., "Describing the Trend of Ammonia, Particulate Matter and Nitrogen Oxides: The Role of Livestock Activities in Northern Italy during Covid-19 Quarantine"

contributes to the secondary formation of PM_{2.5} particles in the atmosphere, which, as noted, are harmful to respiratory and cardiovascular health.¹⁶⁶

6.10.4 Potential Impacts of Leakage from CCS Reservoirs

Leakage from Carbon Capture and Storage (CCS) reservoirs poses a significant risk to the environment, especially when it comes to freshwater aquifers and land. In this section, the varying depths of aquifers and how it impacts their vulnerability to contamination is examined. Additionally, the potential soil and ecological consequences of CO₂ leakage is explored, underlining the need for effective monitoring and mitigation strategies in CCS operations.

Depth Considerations and Freshwater Aquifers

Freshwater aquifers vary significantly in depth, ranging from just below the surface to thousands of feet deep. Due to the weight of the rocks above, a rock's porosity and permeability will generally decrease with depth.¹⁶⁷ Despite this, freshwater has been discovered in rocks at 6,000 feet or lower, and salty water, which is occasionally misinterpreted for tainted freshwater, has been pulled from oil wells at 30,000 feet and below.¹⁶⁸ Most freshwater aquifers are substantially shallower, usually lying between a few hundred feet and several thousand feet below the surface. Precipitation that seeps through the soil and rock strata replenishes these aquifers. Both natural environmental changes and human activity can impact this process.¹⁶⁹

The oil and gas sector uses comparable subsurface injection procedures to CCS, and there is recorded evidence of groundwater pollution from this industry. Therefore, the risk of CO₂ leaking into these aquifers from CCS facilities is real. For example, methane has been detected in groundwater in locations with extensive oil and gas development, such as the Marcellus shale region and the Denver-Julesburg area in Colorado.¹⁷⁰ Although most of this methane is produced naturally, there have been cases where leaky gas and oil wells have been identified as the source of the methane based on its chemical signature.¹⁷¹ Hazardous substances other than methane, including those used in hydraulic fracturing procedures, may flow out of these leaks. One prominent instance concerned the incorrect sealing of a newly dug well in Ohio, which permitted gas to seep into a freshwater aquifer and then into a residence, resulting in an explosion.¹⁷²

Depending on their depth and composition, freshwater aquifers are susceptible to contamination. Aquifers made of permeable materials, such as gravel or sand, are especially vulnerable because

¹⁶⁶ Lovarelli et al.

¹⁶⁷ "Aquifers and Groundwater | U.S. Geological Survey."

¹⁶⁸ "Aquifers and Groundwater | U.S. Geological Survey."

¹⁶⁹ "Aquifers and Groundwater | U.S. Geological Survey."

¹⁷⁰ Allison and Mandler, "Groundwater Protection in Oil and Gas Production | American Geosciences Institute."

¹⁷¹ Allison and Mandler.

¹⁷² Allison and Mandler.

they facilitate the easier passage of water and possibly pollutants. On the other hand, because of their limited water production, more compact rocks like granite are less prevalent as groundwater sources. However, they may provide more protection because of their reduced permeability.¹⁷³ Considering these elements, there is a considerable chance that CO₂ from CCS sites will escape into freshwater aquifers. These events can potentially mobilize harmful materials and acidify groundwater, which would be extremely dangerous for human health, the environment, and wildlife habitats.¹⁷⁴

6.10.4.1 Land and Soil Impacts

Leakage from transport pipelines or CCS reservoirs will result in elevated CO₂ concentrations in soil, which may have numerous effects. There is an intricate relationship between soil CO₂ levels, oxygen availability, and the impact on plant life. In a 2012 study by Al-Traboulsi et al., they found a substantial correlation between lower soil oxygen levels and elevated soil CO₂ concentrations. This led to a hypoxic environment that was harmful to seedling emergence and growth.¹⁷⁵ Depending on the CO₂ concentration, this hypoxia had different effects on seedlings.¹⁷⁶ For example, seeds exposed to soil CO₂ concentrations higher than 50% did not emerge. In comparison, CO₂ levels between 5 and 20% resulted in optimal seedling emergence and survival, albeit with compromised root and shoot development when compared to control plants.¹⁷⁷ There is a negative correlation between seedling growth and soil CO₂ levels and a positive relationship with soil oxygen levels.¹⁷⁸

6.11 Assessing the Net Environment Impact of Energy Sources for Carbon Capture Refineries

The carbon capture process can be very energy intensive and costly, and if the energy is generated from high carbon intensity sources, there is potential to counteract some of the benefits of the carbon capture process by contributing to overall emissions. Emissions could be reduced more economically by combining the use of post-combustion CCS for significant emission sources with fuel switching to lower-carbon alternatives like electricity or hydrogen.¹⁷⁹ However, the carbon intensity of the energy sources driving the CCS process determines the entire environmental impact. Refinery CCS operations frequently employ natural gas; nevertheless,

¹⁷³ Zheng et al., “Potential Impacts of CO₂ Leakage on Groundwater Quality of Overlying Aquifer at Geological Carbon Sequestration Sites.”

¹⁷⁴ Zheng et al.

¹⁷⁵ Al-Traboulsi et al., “Potential Impact of CO₂ Leakage from Carbon Capture and Storage Systems on Field Bean (*Vicia Faba*).”

¹⁷⁶ Al-Traboulsi et al.

¹⁷⁷ Al-Traboulsi et al.

¹⁷⁸ Al-Traboulsi et al.

¹⁷⁹ Sunny et al., “A Pathway Towards Net-Zero Emissions in Oil Refineries.”

even with high capture rates, net emissions reductions must appropriately measure upstream emissions from the gas supply chain.¹⁸⁰ Careful selection of energy sources for CCS in refineries is essential to ensure that emission reductions are real and substantial. It is critical to account for all associated emissions to deliver on the promise of CCS as a viable strategy for achieving long-term environmental goals.

7 Implications and Recommendations

In this section a brief summary of the results and their implications is provided.

As a carbon sequestration method, GCS will certainly play a part in any climate scenario that limits warming below 2 C. What remains a point of contention is whether (and to what extent) GCS should be mobilized as a CDR method via DACCS and BECCS or as a reduction method to allow the continued industrial use of fossil fuels. The implications of developing GCS as a tool for carbon-neutral or potentially even carbon-negative oil and gas should be researched further.

Regarding the permanence of sequestration methods in general, there is a place for both short-term and long-term sequestration in our future. Although short-term methods such as AR and coastal blue carbon have a shorter duration, they are typically cheaper and can be implemented faster than long-term methods such as GCS. This report has concluded that although GCS certainly has a very long intended storage duration, the risk of reversal via leakage is significant enough that it can not be called permanent in the lexical sense of the word. Furthermore, there are many concerns about the viability of GCS that can achieve minimal leakage. Since leakage depends primarily on (i) proper site screening and (ii) proper pressure management, leakage ultimately depends on the quality of GCS regulations in a given region. The largest concern related to site screening is that of large-scale well remediation. The implementation of large-scale well-remediation would impact any economic evaluation of GCS, and should be investigated further to determine the viability GCS with minimal leakage.

¹⁸⁰ Sunny et al.

Appendix

Post-Combustion Capture

Post-combustion capture refers to the capture of CO₂ after the combustion of flue gas but before it is released into the atmosphere.

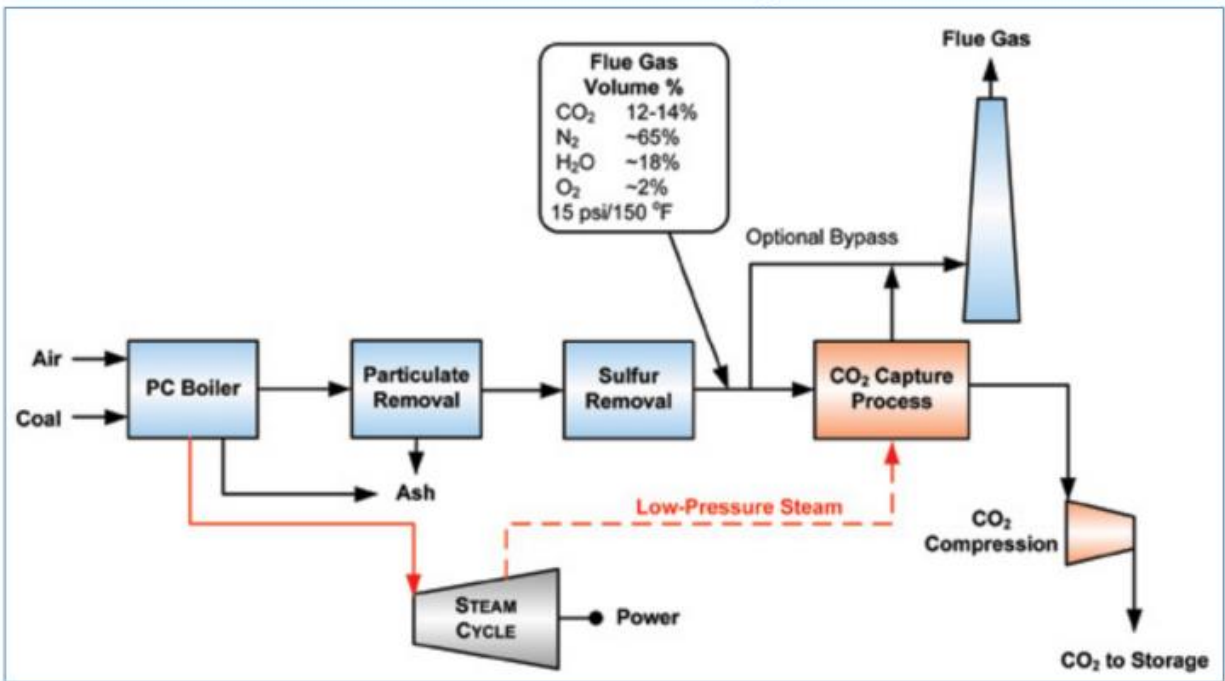


Figure 8: A schematic of a Pulverized Coal Boiler with Post-Combustion CO₂ Capture.

In post-combustion capture, after the fossil fuel is burned to produce energy via a steam engine that drives a turbine/generator, flue gas is produced. In this flue gas, it is primarily N₂ and CO₂ along with trace amounts of other compounds such as sulfur and nitrogen oxides. As a result, the flue gas needs to be treated so that the other compounds do not interfere with carbon capture. In a post-combustion capture system, an amine-based solvent is most commonly used. The gases will first enter a tower where it will flow and come into contact with an amine solution. When flue gas comes into contact with the solvent, it absorbs the CO₂. It chemically reacts with the CO₂ via reversible reactions that produces water-soluble compounds which can be processed later. The other gases such as nitrogen gas will be released into the atmosphere while the CO₂ rich amine is directed into an exchange chamber where it is heated to obtain more than 85% of the CO₂ and the amine. In some cases, should the gases be highly concentrated with

CO₂, more than 90% can be captured.¹⁸¹ The CO₂ is cooled and directed to where compression is done and the amine is recycled for the next use.¹⁸²

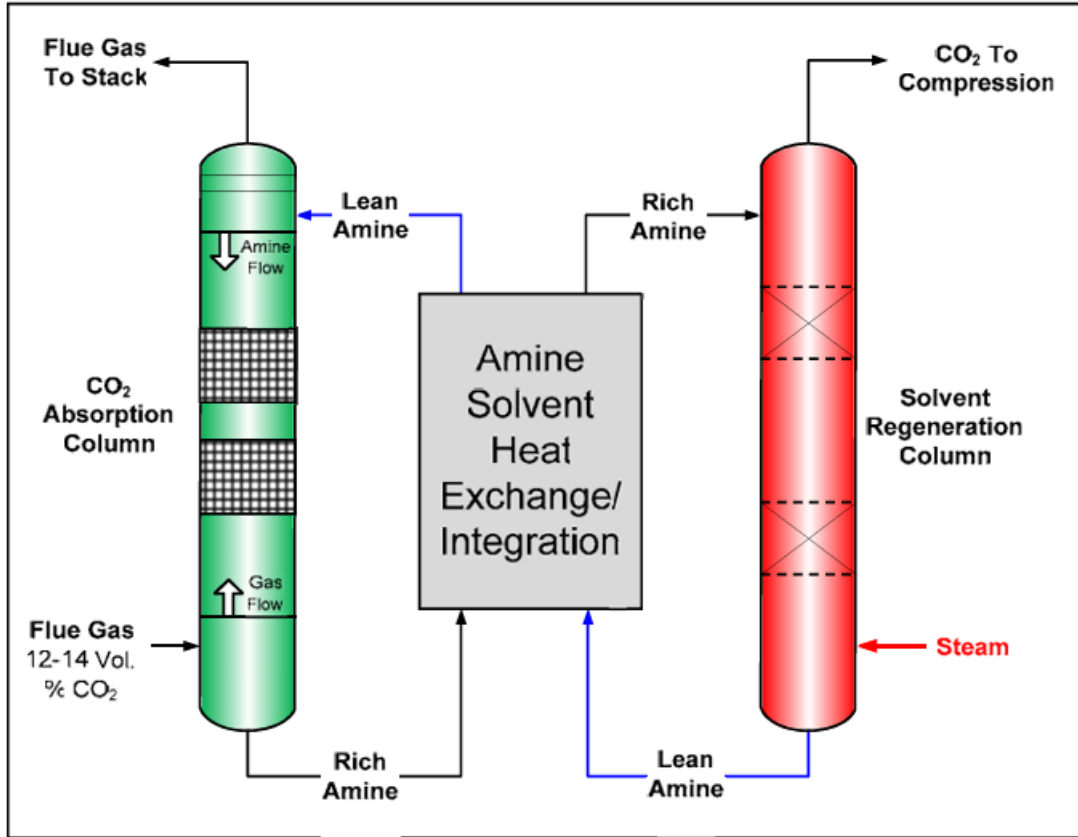


Figure 99: A diagram depicting how amine absorption of carbon dioxide works.¹⁸³

Pre-Combustion Capture

In pre-combustion capture, the capture process takes place before the combustion of fuel takes place. Pre-combustion capture is used in the IGCC (Integrated gasification combined cycle). In this cycle, fuel is typically burned in controlled amounts with limited oxygen to produce syngas so CO₂ can be captured.

The pre-combustion capture process begins with the production of syngas. The fuel is converted into a gaseous state via heat and pressure and the lack of oxygen in a gasifier. The fuel is heated with water and oxygen in an oxygen scarce environment. The amount of oxygen is carefully controlled so only a small

¹⁸¹ Basile and Nunes, *Advanced Membrane Science and Technology for Sustainable Energy and Environmental Applications*, chap. 5.

¹⁸² "Literature Survey of Carbon Capture Technology," n.d.

¹⁸³ "Literature Survey of Carbon Capture Technology," n.d.

portion of fuel burns. This allows for the fuel to be chemically broken apart and results in the following reaction: $3C + H_2O + O_2 \rightarrow H_2 + 3CO$

The production of carbon monoxide is referred to as synthetic gas (syngas) and can potentially include other compounds such as hydrogen sulfide, or carbonyl sulfide and carbon dioxide. These will be produced depending on the fuel characteristics and the conditions for combustion, and the volume of CO₂ in the syngas will typically be under 20% of the gas. After the syngas is removed of any impurities such as ash, the syngas is combusted using a conventional combustion turbine.

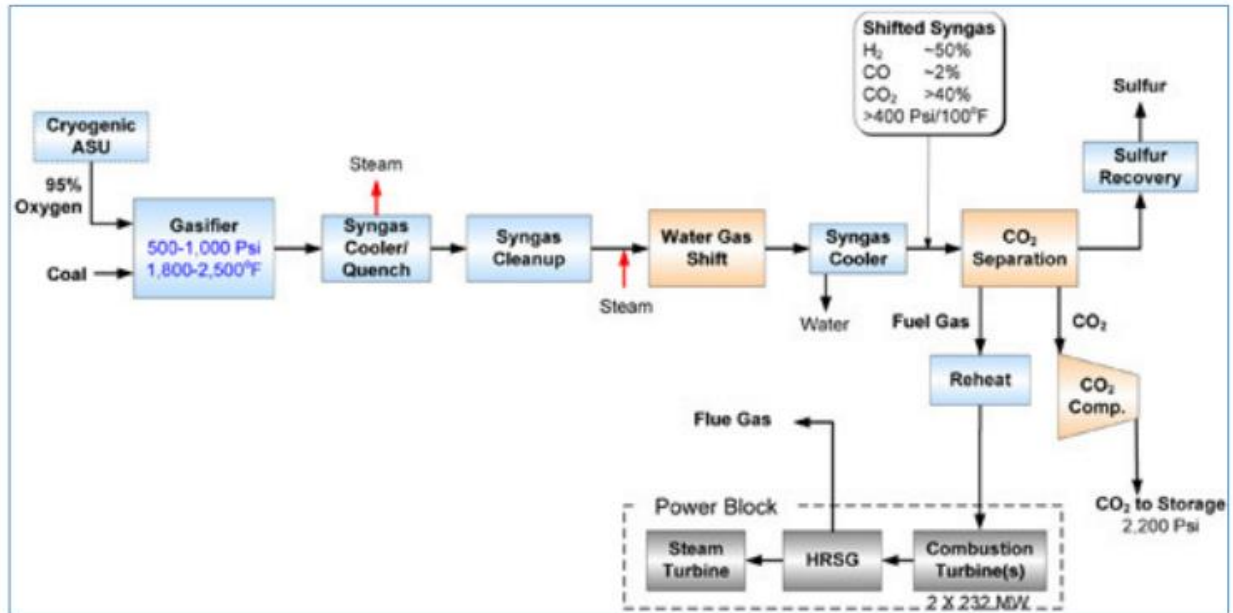


Figure 10: A schematic of Pre-Combustion CO₂ Capture for an IGCC Power Plant¹⁸⁴

Before it is combusted, however, the CO₂ has to be captured. The process of pre-combustion capture involves the increase of CO₂ in the syngas from other compounds such as carbon monoxide. To achieve an in CO₂ volume in the syngas, a water-gas shift process is used represented by the following reaction: $CO + H_2O \rightarrow H_2 + 3CO_2$. The CO₂ from this reaction is separated from the H₂ gas. CO₂ can be absorbed via a physical solvent, solid sorbent, or a membrane. This allows for more carbon to be captured as opposed to it being combusted with syngas. Currently, the glycol-based Selexol process and methanol-based Rectisol process can be and are used for pre-combustion carbon capture and is commercially available with an estimated cost of around \$60 per tonne of CO₂.¹⁸⁵

In the Selexol process, the syngas first enters an absorber where H₂S is removed using a CO₂ rich solvent from the CO₂ absorber. The semi-treated gas then enters a second absorber where CO₂ is removed using solvent streams. The treated gas is then sent for combustion. The CO₂ rich gas

¹⁸⁴ "Literature Survey of Carbon Capture Technology."

¹⁸⁵ "Pre-Combustion Carbon Capture Research."

sophisticated, it will cost more, but will be a net positive because of its high CO₂ concentrations compared to post or pre-combustion capture.¹⁸⁷

Compressors

In centrifugal compressors, it can accommodate the heating and cooling of the gas when it is being compressed. Centrifugal compressors work by increasing the pressure of the gas by adding kinetic energy (velocity) to the gas as it flows through the impeller, the rotating element of the centrifugal compressor, responsible for imparting kinetic energy to the gas and accelerating it outwards. After, the high-speed gas leaves the impeller and enters the diffuser where it expands, slows down and pressurizes. When it is pressurized, it leaves the diffuser and is discharged.¹⁸⁸ There are two types of centrifugal compressors, an integrally geared compressor, and a beam-style compressor.

The integrally geared compressor is driven by an electric motor which drives different gears containing centrifugal compressors on each end of the compressor. During low pressure stages, it will run at lower speeds and during high pressure stages, it will run at higher speeds. This allows for cooling between each stage which will allow for compression. However, a downside to an integrally geared compressor is its size and reliability issues due to the many moving parts and gears.¹⁸⁹



Figure 1210: A 3D render of an integrally Geared Compressor

The beam-style compressor is more commonly used. It can be configured in a one way or back-to-back configuration, where one way allows for the gas to only pass through one way and back-to-back allows for the gas to go back and forth through the compressor. Configuring the compressor in the back-to-back configuration allows for cooling between different sections and the body of the compressor, which is much more efficient. The gas is constantly cooled after

¹⁸⁷ "Literature Survey of Carbon Capture Technology," n.d.

¹⁸⁸ byun, "How Do Centrifugal Compressors Work?"; Araner, "What Is a Centrifugal Compressor and How Does It Work?"

¹⁸⁹ "Literature Survey of Carbon Capture Technology," n.d.

each stage in the flow path of the compressor via a cooling jacket. In the figure, the CO₂ is represented as red and the cooling jacket is blue.¹⁹⁰

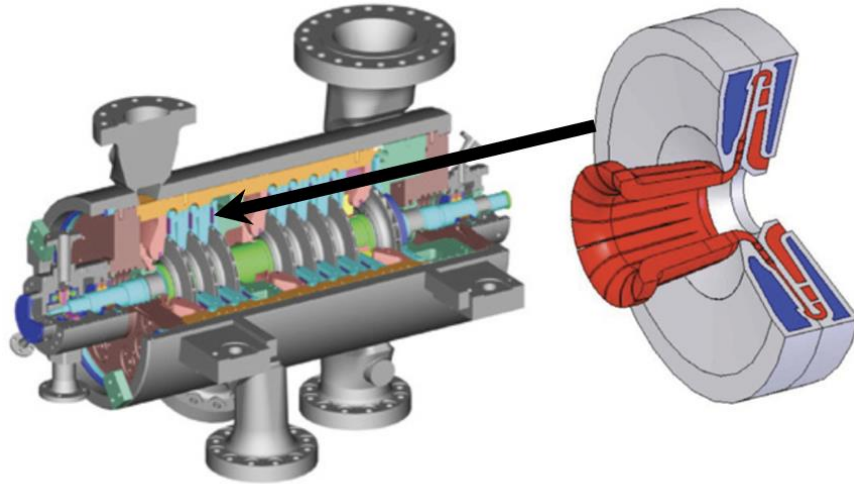


Figure 1311: A diagram of the internals of a Beam-Style Compressor

¹⁹⁰ "Literature Survey of Carbon Capture Technology."