American Journal of Climate Change, 2023, 12, 579-627
https://www.scirp.org/journal/ajcc
ISSN Online: 2167-9509
ISSN Print: 2167-9495

Carbon Dioxide Sequestration Methodothologies—A Review

Gregory Mwenketishi, Hadj Benkreira, Nejat Rahmanian*

School of Engineering, Faculty of Engineering and Digital Technologies, University of Bradford, Bradford, UK
Email: tarteh9@gmail.com, *n.rahmanian@bradford.ac.uk

How to cite this paper: Mwenketishi, G., Benkreira, H., & Rahmanian, N. (2023). Carbon Dioxide Sequestration Methodothologies—A Review. *American Journal of Climate Change, 12,* 579-627.
https://doi.org/10.4236/ajcc.2023.124026

Received: July 15, 2023
Accepted: November 24, 2023
Published: November 27, 2023

Abstract

The process of capturing and storing carbon dioxide (CCS) was previously considered a crucial and time-sensitive approach for diminishing CO_2 emissions originating from coal, oil, and gas sectors. Its implementation was seen necessary to address the detrimental effects of CO_2 on the atmosphere and the ecosystem. This recognition was achieved by previous substantial study efforts. The carbon capture and storage (CCS) cycle concludes with the final stage of CO_2 storage. This stage involves primarily the adsorption of CO_2 in the ocean and the injection of CO_2 into subsurface reservoir formations. Additionally, the process of CO_2 reactivity with minerals in the reservoir formations leads to the formation of limestone through injectivities. Carbon capture and storage (CCS) is the final phase in the CCS cycle, mostly achieved by the use of marine and underground geological sequestration methods, along with mineral carbonation techniques. The introduction of supercritical CO_2 into geological formations has the potential to alter the prevailing physical and chemical characteristics of the subsurface environment. This process can lead to modifications in the pore fluid pressure, temperature conditions, chemical reactivity, and stress distribution within the reservoir rock. The objective of this study is to enhance our existing understanding of CO_2 injection and storage systems, with a specific focus on CO_2 storage techniques and the associated issues faced during their implementation. Additionally, this research examines strategies for mitigating important uncertainties in carbon capture and storage (CCS) practises. Carbon capture and storage (CCS) facilities can be considered as integrated systems. However, in scientific research, these storage systems are often divided based on the physical and spatial scales relevant to the investigations. Utilising the chosen system as a boundary condition is a highly effective method for segregating the physics in a diverse range of physical applications. Regrettably, the used separation technique fails to effectively depict the behaviour of the broader significant system in the context of water and gas movement within porous media. The limited efficacy of the technique in capturing the behaviour of the broader relevant system can be attributed to the intricate nature of geological subsurface systems. As a result, various carbon capture and storage (CCS) technologies have emerged, each with distinct applications, associated prices, and social and environmental implications. The results of this study have the potential to enhance comprehension regarding the selection of an appropriate carbon capture and storage (CCS) application method. Moreover, these findings can contribute to the optimisation of greenhouse gas emissions and their associated environmental consequences. By promoting process sustainability, this research can address critical challenges related to global climate change, which are currently of utmost importance to humanity. Despite the significant advancements in this technology over the past decade, various concerns and ambiguities have been highlighted. Considerable emphasis was placed on the fundamental discoveries made in practical programmes related to the storage of CO_2 thus far. The study has provided evidence that despite the extensive research and implementation of several CCS technologies thus far, the process of selecting an appropriate and widely accepted CCS technology remains challenging due to considerations related to its technological feasibility, economic viability, and societal and environmental acceptance.

Keywords

Aquifer, Carbon Subsurface Storage (CSS), CO_2 Sequestration, Environment, Geological Storage, Carbon Capture and Storage (CCS)

1. Introduction

Previous studies have emphasized Anthropogenic CO_2 as well as other greenhouse gas (GHG) emissions that have indeed been recognised as the primary cause of global warming and climate change (MacDowell et al., 2013). The reports published by IEA 2016 and NASA 2017 confirmed that CO_2 concentrations in the atmosphere have risen from 280 ppm in the mid-1800s to approximately 404 ppm in 2016, resulting in a nearly 1˚C increase in mean earth temperature above the pre-industrial levels. This temperature increase, which occurred between 1901 and 2010, resulted in a 20 cm increase in worldwide mean sea level (UK Met Office 2016). It is widely acknowledged that the average global temperature increase from pre-industrial rates must be maintained far below 2˚C by 2100 to avoid catastrophic climate change disasters (IPCC, 2005). As a result, the European Union and the G7 countries have set a goal of reducing GHG emissions by at least 80% from 1990 levels by 2050 (IEAGHG, 2009a) and (European Climate Change Foundation, ECF, 2010).

Power plants and other energy-intensive sectors are regarded as significant CO_2 emitters and are required to reduce their produced CO_2 emissions substantially. The high carbon intensity of the power industry (World Nuclear Association) 42%, is due to the significant proportion of coal-fired facilities in the worldwide energy supply. Furthermore, the development of shale gas in North America has resulted in an increase in coal production and exports from the United States. As a result, it resulted in a significant decrease in coal pricing, which in turn resulted in a greater proclivity for coal-based power generation (Hanak et al., 2015). Therefore, de-carbonization of the electricity and manufacturing sectors is critical to meeting emission reduction goals.

CCSI in 2011 provided evidence for Carbon Capture and Storage (CCS) as the most crucial method for decarbonizing the electricity and industrial sectors. It is predicted that CCS alone may contribute almost 20% of the decrease by 2050 and that excluding CCS can result in a 70% increase in the worldwide cost of meeting emission reduction goals (UK DECC, 2012). Permanent CO_2 sequestration is the US-DOE United States Department of Energy's plan. USGS VSP Vertical Seismic Profile XRD (X-Ray Diffraction) is the final step in the CCS chain and could be implemented using a range of strategies, primarily mineral carbonation, oceanic, and underground geological storage along with saline aquifers, oil and natural gas reservoirs, inaccessible coal seams, and other geological porous media. According to Yamasaki (2003), the critical criteria of a viable CO_2 storage option are net CO_2 emission reduction, high storage capacity, long-term CO_2 isolation (at least several hundred years), acceptable cost and energy penalty, and little environmental effect. However, public acceptance/embracing is another essential element that may have a significant impact on the technology's adoption (Mabon & Shackley, 2013).

Several reviews, including Bachu (2015) and Bai et al. (2015) have addressed various features of CO_2 storage in the past. However, particular areas have yet to be addressed or thoroughly examined. Although CO_2 storage is a technically established technique, further deployment is hampered by ambiguity and challenges related to estimating storage capacity, tracking verification and monitoring of CO_2 during and after injection, characterising potential injection-induced seismicity, and standardising storage evaluation criteria, and practical, ethical mechanisms. Furthermore, CO_2 storage is a dynamic subject, and current success and growth must be examined and addressed as more information becomes available.

Within the framework of CCS, there exist various potential avenues for the sequestration of CO_2. These options include underground geological storage, deep ocean storage, and mineral carbonation (IPCC, 2005). Underground geological storage, in particular, encompasses several subcategories, such as saline aquifers, depleted oil and gas reservoirs, un-mineable coal seams, hydrate storage, and CO_2 storage within enhanced geothermal systems (Na et al., 2015).

This section offers a thorough examination of each storage approach and afterwards delineates potential avenues for future research that can enhance the existing knowledge.

CCS is widely recognised as a crucial approach for achieving decarbonization in the manufacturing and energy sectors (GCCSI, 2011). According to estimates, the implementation of CCS technology alone has the potential to achieve a reduction of about 20% in emissions by the year 2050. Furthermore, the absence of CCS might result in a significant rise of up to 70% in the overall global cost required to meet emission reduction targets (DECC, 2012). The final stage in the CCS process involves the long-term containment of CO_2. This can be accomplished through several methods, such as mineral carbonation, oceanic storage, and underground geological storage. The latter includes storing CO_2 in saline aquifers, depleted oil and gas reservoirs, un-mineable coal seams, and other geological formations. The primary attributes of a viable CO_2 storage solution encompass a net decrease in CO_2 emissions, substantial storage capacity, extended isolation of CO_2 for a minimum of several centuries, cost-effectiveness and minimal energy penalty, as well as mitigated environmental consequences (Yamasaki, 2003). However, the acceptance and embrace of the technology by the general population is another crucial component that can have a substantial impact on its implementation (Mabon & Shackley, 2013).

Multiple scholarly articles have examined many facets of CO_2 storage (Bachu, 2015) as indicated in **Appendix 1**, **Table A1**. Nevertheless, certain aspects have not yet been addressed or thoroughly examined. Although CO_2 storage has been demonstrated to be a technically viable technology, its widespread implementation is hindered by various uncertainties and challenges. These include difficulties in accurately estimating storage capacity, effectively tracking, verifying, and monitoring CO_2 during and after injection, characterising the potential for induced seismic activity resulting from an injection, establishing standardised criteria for evaluating storage sites, and implementing effective ethical mechanisms. Furthermore, the topic of CO_2 storage is rapidly advancing, necessitating a comprehensive examination and discourse on recent advancements and developments.

In course of preparing this paper, a comprehensive and critical review has been carried out on the most up-to-date CCS methods and to identify their application, limitations and potential future work through research analyses.

2. CO_2 Sequestration Methods

According to the IPCC Special Report from 2005, different CO_2 sequestration methods that could be used for stored CO_2 include deep ocean, geological and mineral carbonation, several subterranean reservoir formations alternatives do exist, including saline aquifers, depleted oil and gas reserves, unreachable coal seams, hydrate storage, and CO_2 inside improved geothermal systems (Bachu et al., 2000; Han & Winston Ho, 2020).

Figure 1 and **Appendix 1** presents a comprehensive review of significant large-scale CSS initiatives that have been implemented globally. In the majority of these operations, CO_2 has been sequestered in saline aquifers or utilised for enhanced oil recovery (EOR) purposes. The security of containment is a critical determinant for the success of storage projects. Therefore, it is imperative to

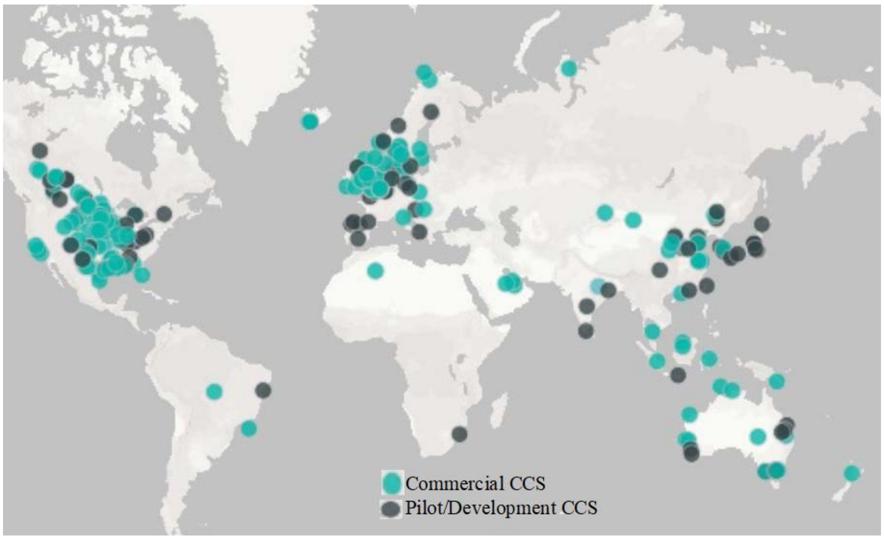


Figure 1. Worldwide CCS initiatives encompassing large-scale commercial projects that have been previously operational and pilot development operations (MIT, 2015; Shukla et al., 2010; Global CCS Institute—CO_2RE).

consistently enhance the process of selecting and characterising sites, determining technical operation parameters, developing monitoring and verification systems, and conducting quantitative risk assessments. Taking a comprehensive approach to these variables will serve as the foundation for developing suitable technical rules and fostering a favourable public image, thus facilitating the smooth implementation of large-scale CSS operations.

The utilisation of underground geological storage has been widely regarded as the most feasible method for sequestration. Geological storage is considered a more advantageous method of sequestration when compared to carbonation and oceanic storage due to various factors. These factors encompass economic considerations, site accessibility (particularly relevant to ocean and mineral sequestration), as well as concerns related to the security of stored CO_2 and the potential negative environmental consequences associated with mineralisation and ocean storage. This section will provide a full discussion of many potential geological storage alternatives, as depicted in **Figure 2** below.

2.1. Storage in Subsurface Reservoir Formations

The most workable sequestration option is an underground geological storage system. The security of the CO_2 being stored, as well as the detrimental effects on the ecosystem, are some of the key points that set geological storage from CO_2 mineralization and marine storage. **Figure 2** depicts various possible geological storage systems that are considered to be effective and would need further investigation for better understanding.

Considering that available information in the overwhelming CSS can managed at the vast majority of locations efficiently and safely, there is still a possibility that storage facilities might be put in danger by factors such as generated seismicity if these factors are not well analysed.

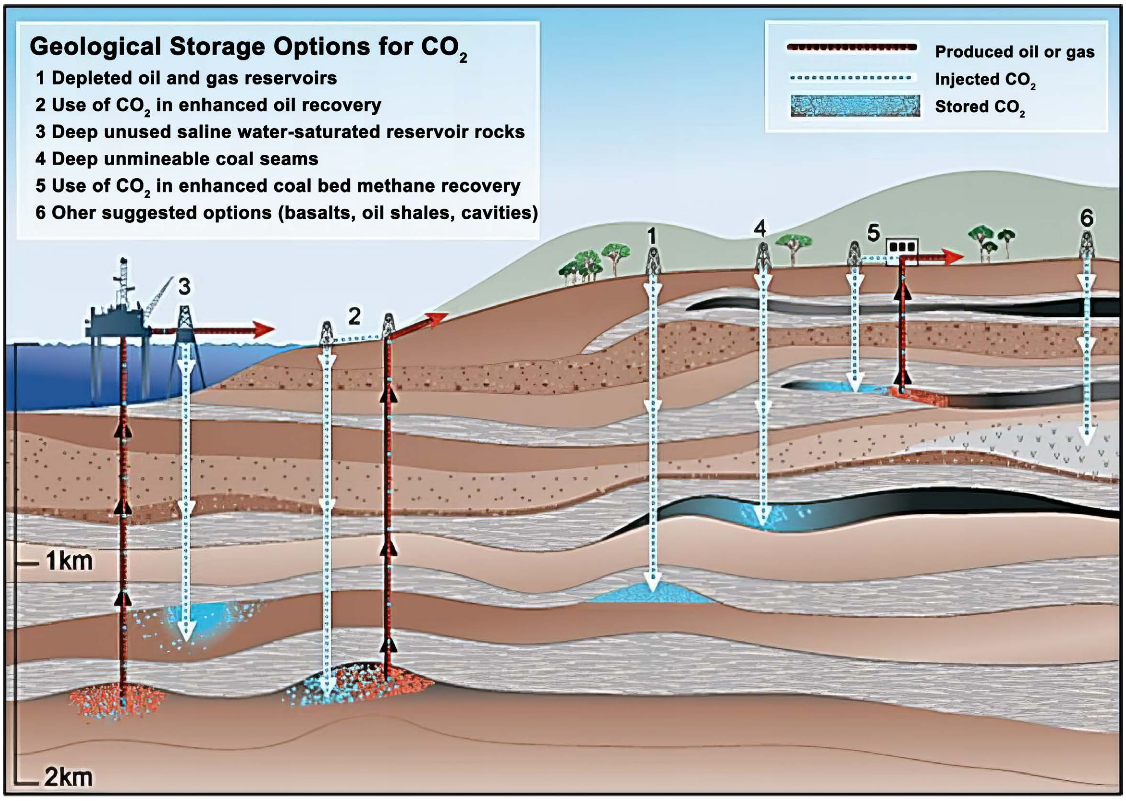


Figure 2. Schematic illustration of various geological storage systems for CO_2 (Courtesy CO_2CRC, 2015).

2.1.1. Brine Aquifers

Several researchers have acknowledged that storing CO_2 in deep salty aquifers represents one of the most successful strategies for reducing CO_2 in the atmosphere (Li et al., 2023; Javaheri & Jessen, 2011; Yang et al., 2013; Frerichs et al., 2014; Burnol et al., 2015), due to its already available technological and significant possible storage capacity (Bachu et al., 2000). However, most saline aquifers are presently unsuitable for other synergistic or competing uses (Trémosa et al., 2014) especially in highly populated nations (Procesi et al., 2013; Quattrocchi et al., 2013). The absence of facilities including wells for CO_2 injection, surface handling equipment, and transportation pipeline networks makes many salty aquifers less desirable as potential storage reservoir formation alternatives at the moment (Li et al., 2023).

Recently, the topic of discussion has been the potential for CO_2 to be stored in salty aquifers (Bachu, 2003; Wei et al., 2022) in combination with EOR storage (Boundary-Dam-Apache). These studies address topics including site description, as well as long-term planning, according to (Bachu, 2010) as well as the range of complementary and competing subterranean uses (Procesi et al., 2013).

Because of their vast pore volume and high permeability, aquifer reservoir formations can hold massive amounts of CO_2, cutting down on an overall number of CO_2 injection wells required and easing pressure dissipation (Shukla et al., 2010). Upon flowing into the storage reservoir formation, supercritical CO_2 dislocates brine in the pore spaces and initiates a chain reaction with the formation's minerals (groundwater, gas, and rocks) that lead to either formation of different chemical substances or the breakdown of current minerals (Le Gallo et al., 2002; Cantucci et al., 2009). Mineral formation and dissolution may alter rock porosity and, as a result, the capacity of the storage reservoir (Wdowin et al., 2013).

Previous studies (Tapia et al., 2018) have shown that supercritical CO_2 has a density of approximately 0.6 - 0.7 g/cm^3 in saline reservoirs, the low density can influence the uprise movement of CO_2 towards the cap-rock because of buoyancy forces due to density variation.

According to previous studies (Armitage et al., 2013), a large aquifer storage basin with a high sealing capacity of the cap-rock is necessary for long-term and stable CO_2 storage. Given that cap-rock, a formation at the reservoir's top with low to very low permeability (Fleury et al., 2010) should operate as a seal to prevent CO_2 migration from the storage deposit below. With its low permeability, cap-rock is crucial for preventing CO_2 from escaping the retention reservoir and minimizing leakage. Another essential element that may result in cap-rock integrity loss and CO_2 leakage is the existence of unrecognised fracturing and fault-plane. However, from the review, no previous researcher has investigated further study on the impacts of CO_2-brine reactivity on injectivity and the fracturing network and fault plane for CO_2 storage, as such, a thorough research study is required to investigate the effect of this reactivity and previous faults on cap-rock stability (Buttinelli et al., 2011).

Figure 3 depicts the four major trapping processes that may safely handle CO_2 storage:

a) Structural/stratigraphic

b) Residual

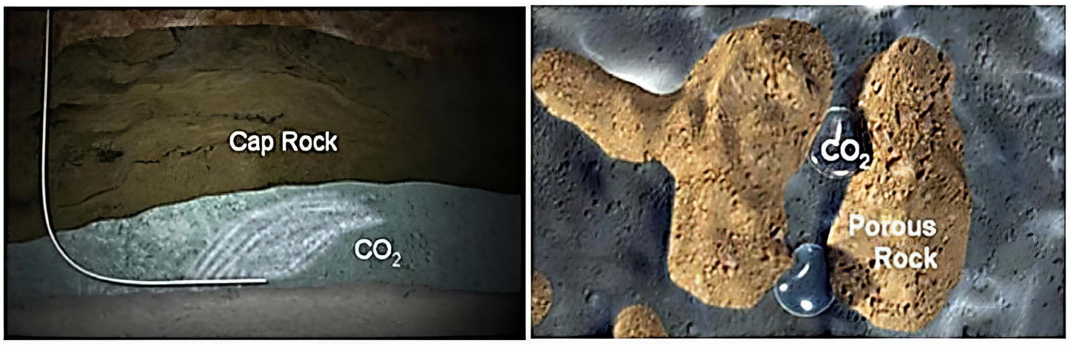
c) Solubility

d) Mineral trapping.

Stratigraphical and/or Structural Trapping: When CO_2 is introduced into a geological formation, it may move to the top and get trapped behind an impermeable top seal (Kim et al., 2017) where it can remain as a free phase that cannot go beyond or access the cap-rock pore region except by slow diffusion or fractures as illustrated on **Figure 3(a)**. It's the most common kind of subsurface trapping system.

CO_2 Rock Pores Capturing: Injection of CO_2 into aquifer porous rock gives rise to fluid displacement due to differences in density. **Figure 3(b)** shows how the fluid displaced by the CO_2 flows, returns, disconnects, and traps the remaining CO_2 within pore spaces. It has been observed that the method occurs exclusively when water drainage processes occur during CO_2 injection, rather than inside structural and stratigraphic traps (Bachu et al., 2007).

Solubility trapping: CO_2 dissolves in brine through the chemical process of solubility, plummeting the quantity of CO_2 gas-phase (**Figure 3(c)**). The density



(a) Structural/stratigraphic trapping **(b) Residual trapping**

(c) Solubility trapping **(d) Mineral trapping**

Figure 3. Illustrate the major 4 CO_2 trapping subsurface systems (Zhao et al., 2014).

of brine is increased by the solubility of CO_2 and this may cause gravitational instability, hastening the transition of injected CO_2 to CO_2-lean brine (Kneafsey & Pruess, 2010).

Trapping due to Mineral: CO_2 undergoes chemical interactions with minerals and salty water found around the rock's periphery. Carbonate precipitation occurs as a consequence of these chemical reactivities and has the effect of sequestering CO_2 in an inert lesser phase across a specific subsurface geological timeframe, as demonstrated in **Figure 3(d)** above (Bachu, 1998). It is a more gradual process than the solubility capturing that takes place over a longer geologic period (Gunter et al., 2004; Sundal et al., 2014).

Although a number of studies have argued that storing CO_2 in salty aquifers would be more effective than CO_2 is often stored in depleted oil and gas fields, these assessments neglect to take into consideration the expenses connected as a result of the use of storage in saline reservoirs. In many instances, hydrocarbon fields already have production facilities in place, which, with only relatively modest adjustments, may be modified to meet storage operations. These changes can be made in order to accommodate storage activities. In addition, they have been well defined throughout the stages of crude oil exploitation, and they may employ CO_2 for storage as well as EOR. As a consequence, it is possible that storing CO_2 in hydrocarbon formations is better than storing it in saltwater aquifers.

2.1.2. Hydrocarbon Reservoir Formations

The sequestration of CO_2 in depleted oil and gas reservoirs is widely recognised as one of the most efficient techniques of CO_2 storage. Among these advantages are the following: 1) Drained hydrocarbon reservoirs have been the subject of substantial research both before and during the hydrocarbon exploring period, including research about their storage capacity; 2) Both onshore and offshore infrastructural facilities, existing infrastructure, including CO_2 injection wells and transportation, may be used with little modification for the storage process (Sigman et al., 2021); 3) If this was not the case, CO_2 gas injection to enhance oil recovery would have been less attractive and ends many years ago. Suitable hydrocarbon field data as an analogue may be utilise in illustrating the efficacy of cap-rock across geologic timeframe to strengthen oil and gas reservoirs (Heinemann et al., 2016).

Reservoir rocks and brine properties are similar and commonly found in both hydrocarbon reservoirs and deep aquifer storage systems (Li et al., 2014). Oil and gas reservoirs, on the other hand, may be considered for EOR, making them more economically advantageous than saline aquifers (Zangeneh et al., 2013; Gao et al., 2016). Because the worldwide average recovery factor from a typical oilfield is about 40% (BGS, 2017), usually, many barrels of oil are still in the hydrocarbon reservoirs. It's the primary motivation for the global deployment of EOR. However, technological deployment difficulties remain challenging, although these issues may have been foreseen and handled throughout the exploration and production phase of a field, they have just recently come to light.

Gas injection is the most frequently utilised among the current EOR alternatives such as gas, thermal, chemical, and plasma-pulse injection techniques. Miscible gases (CO_2, nitrogen, and natural gas) are injected into the reservoir using the gas injection process to decrease the interfacial tension between oil and water and increase oil displacement efficiency while preserving reservoir pressure. CO_2 injection seems to be the optimal choice because it may reduce oil viscosity and is less expensive than liquefied natural gas (Jaramillo et al., 2008). More CO_2 for improved oil recovery is anticipated to be accessible from vital gathering point sources with the introduction of CCS technology (IPCC, 2005). It has been claimed, for example, that the use of CO_2 for EOR has resulted in an increased output of about 260,000bopd in the U.S.A (GCCSI, 2017).

The International Energy Agency (IEA) (2015) set out the following as the primary criteria for the implementation of CO_2 oil recovery support (EOR) projects:

1) Additional site characterization involves investigating potential leakage risks, such as the condition of the cap rock and any abandoned wells with integrity problems.

2) Additional evaluations of surface processing plants' fugitive and discharging emissions

3) Leakage rates may be estimated from specific locations and the normality of the reservoir's behaviour can be determined by increased monitoring and field surveillance.

In addition to the criteria mentioned above, governments must address legal problems and enact laws to cover storage facility operations. These issues arise because CO_2-EOR and CO_2 permanent storage fall under two distinct regulatory umbrellas, the former focuses on resource recovery, whereas the latter is concerned with waste management Marston (2013). Legal issues might arise, for instance, regarding the proper decontamination of oil left in situ after production ceases, if hydrocarbon recovery is prioritised. Such a scenario may be jurisdiction-specific and especially significant when onshore mineral and storage rights are owned privately.

One of the critical variables that must be rigorously defined before a CO_2-EOR project is initiated involves the kind and number of contaminants in CO_2 streams. Depending on the CO_2 source and the accompanying collecting procedures, a variety of contaminants might be contained as part of the CO_2 injection fluid (Porter et al., 2015). The permissible impurities and concentrations are determined by a mix of transit, storage, and economic factors. CO_2 streams must meet a minimum purity standard of roughly 90% vol (Jarrell et al., 2002). In the case of CO_2, increasing impurity levels may cause the phase boundaries to move to even higher pressures, which demonstrates the requirement for higher injection pressures to keep the injected CO_2 in a higher concentration. It has also been established that non-condensable contaminants lower CO_2 storage capacity by a factor that is larger as compared to the mole percentage of contaminants present in the CO_2 injection system (IEAGHG, 2011).

The most typical issue connected to contaminants is corrosion. Due to the corrosive effects that impurities (such as SO_2, NO_2, CO, H_2S, and Cl) may have on transportation and injection systems, it is essential to limit the quantity of contaminants on a scenario rationale. Additionally, it is essential to develop feasible mitigation solutions for potential problems (Porter et al., 2015). It is important to note that even though certain impurities such as CO, H_2S, and CH_4 have a naturally occurring propensity to be combustible, safety considerations for combustibility are not typically factored into the evaluation of safety measures. This is because it is highly unlikely that the CO_2 injection stream will be combustible due to the low quantities of the impurities in question. Another issue that may influence the effectiveness of the CO_2-EOR process is an excessive concentration of O_2 in CO_2 streams. The presence of O_2 in the reservoir may stimulate microbial activity (Porter et al., 2015), which can ultimately lead to operational problems such as injection obstruction, oil deterioration and oil souring.

The previous studies (Igunnu & Chen, 2014) have connected environmental problems of EOR with volumes of water production that may include radioactive compounds and dangerous heavy metallic substances. Failure to implement an appropriate waste management and disposal strategy implemented, these chemicals may pollute drinkable water sources. Although restrictions exist, governments must ensure that operators follow current laws when brine re-injection for recovery is permitted. For example, White (2009) provided evidence to show that the Weyburn-Midale CO_2 storage project in Canada is an example of how collected in the Weyburn oilfield, CO_2 might be used for EOR and retention. Not only does this procedure recover a significant amount of previously unrecovered oil, but it also increases the oilfield's useful lifespan by 20 - 25 years (Thomas, 2008). According to Zaluski et al. (2016), Verdon (2016) long-term surveillance, generated seismicity evaluation of CO_2's impact on the reservoir and the fluids' mutual effect, oil and minerals have been the primary focuses of CO_2-EOR research (Hutcheon et al., 2016). The Weyburn case history inspired (Cantucci et al., 2009) to study the geochemical equilibrium between brine and oil and develop a biogeochemical model for CO_2 storage in underground reservoirs. A hundred years into the future, they predicted precipitation and disintegration processes based on research into reservoir formation during CO_2 injection. During the first year of the simulation, they discovered that the two most significant chemical processes taking place in the reservoir were those involving CO_2 and the dissolution of carbonate. Furthermore, the development of chemical characteristics over time indicated that CO_2 might be securely stored via mineral and solubility trapping.

Perera (2016) acknowledges that though the CO_2-EOR method has substantially improved oil recoveries, further improvement is needed using the following strategies: 1) Using numerical evidence (Tenasaka 2011) proved that this was possible within the normal range of CO_2 injection. In the San Joaquin basin, scientists injected around 2.0HCPV (hydrocarbon pore volume) of CO_2 to prove that there was a greater possibility to extract more oil, almost 67% of the originally present oil (OOIP) was recovered. In addition (Tenasaka 2011) demonstrated that there was a greater recovery of oil from his numerical methodology; 2) Using a better and innovative CO_2 flooding design and well management can positively influence more oil recovery from the reservoir; 3) Increasing the mobility-ratio by raising water's viscosity (Thomas, 2008). Minimising miscibility pressure using miscibility-enhancing agents (Kuuskraa & Ferguson, 2008).

2.1.3. In-Accessible Coal Seams

An additional option for sequestering human-caused CO_2 is the use of inaccessible coal seams. Since cleats are present inside the coal matrix, the system is somewhat permeable. In addition, the matrix of coal is full of tiny holes (micropores) that may take in a lot of air. Coal has a greater affinity for CO_2 in the gas phase than methane, and this is the basis for the CO_2 trapping process. According to (Shukla et al., 2010), this means that the methane output could be increased while the CO_2 was permanently stored. Thus, large amounts of CO_2 may be stored while commercial unconventional shale methane (CBM) processes are made more productive and profitable (Krooss et al., 2002; Gilliland et al., 2013). It should be underlined that although CO_2 increases CBM synthesis, the overall quantity of methane generated is not always higher than without the addition of CO_2. The International Energy Agency Working Group on Greenhouse Gases

(IEAGHG, 2009b) provided an overview of the essential technical parameters needed for the effective implementation of enhanced coal seam production, which include: 1) The homogeneity Reservoir; 2) Threshold of fractures and fault planes; 3) Upper depth limit; 4) Coal geomorphology; 5) Permeability adequacy.

Two experimental locations, the Alberta Carbon Trunk Line (ACTL) in Canada with the San Juan Basin pilot in the United States, have reportedly used the ECBM approach, the conclusion of the evaluations for the Alberta project (Krooss et al., 2002): 1) Even in constrained reservoirs, continuous CO_2 injection is feasible; 2) Injection may be performed notwithstanding a decrease in injectivity; 3) Expected Significantly Enhanced CBM Production; 4) The injected carbon dioxide stays in the reservoir, boosting sweep efficiency (Lakeman, 2016).

Key findings from the San Juan Basin pilot study revealed that methane recovery exceeded the predicted ultimate primary production. Second, the pilot project was not cost-effective because of the price of gas at the time it launched. However, if the price of gas continues to climb in the years to come, the pilot project may end up being lucrative; thirdly, because fuel prices were high when the project was first implemented, the trial project was not profitable. An additional pilot study of a Coal field is being done in the Appalachian Basin, with a focus on a variety of surveillance and verification techniques, and accounting (MVA) methods are being utilised to understand better storage complexity, (Gilliland et al., 2012). Furthermore, the possible ECBM implementation, as well as the significant variations in output across nearby wells with the same stratigraphic, has been studied in the beginning. However, further research is needed to characterise and portray such disparities adequately.

While CO_2 EOR has been used successfully for years in the upstream oil and gas sector, the utilisation of CO_2 during ECBM is still limited in its recognition. There are still many unknowns when it comes to ECBM recovery, however, the current understanding of how the CO_2 EOR process works could help alleviate some of those worries. For example, the creation of technically recoverable shale in ECBM could need a look at already-existing technology from the oil industry that might be converted with very little work. Existing well materials may be utilised as a baseline for good integrity in ECBM production following suitable changes. Furthermore, field and reservoir management techniques processes, such as risk monitoring and evaluation may be modified from those already in place and used at any point in the lifetime of a project.

2.1.4. Subsurface Basalt Formations

There exists a considerable body of literature on subsurface basalt deposits within central igneous provinces, and many researchers McGrail et al. (2006), Pollyea et al. (2014) and Matter et al. (2016) have suggested subsurface basalt deposits as a possible CO_2 storage solution. Basaltic rocks make up around 8% of the continents and a large portion of the ocean bottom. As a result, basaltic rocks have a massive theoretical CO_2 storage capacity (Anthonsen et al., 2014). One of the most important advantages of such rocks' potential to store CO_2 is that their physical and chemical characteristics, as well as the amount of divalent metal ions they contain, may fix CO_2 during past geological periods (Van Pham et al., 2012). Permeability and porosity of Basalt flows, on the other hand, are very variable and often consist of an interior low-permeability region surrounded by periphery regions with high permeability. That said, the rubbly zones between separate flows are the most critical portions of a basalt sequence for CO_2 storage.

Complimentary CO_2 injected into subsurface basalts (the CarbFix pilot scheme, Iceland) may replace water in the rock's pore spaces and cracks (Matter et al., 2011). The decrease in water content may impede basalt carbonation and hydration. Therefore, it may be possible to inject CO_2 and the right amount of water into the same reservoir based on the following points: 1) Because it offers sufficient depth, denser CO_2 liquid may sink, which delays the release of CO_2 back into the atmosphere; 2) It makes it possible to form stable carbonates in a shorter amount of time than would normally be required by geologic processes; 3) It prevents acidic basement fluids from rising via an impervious sediment layer; 4) It can be converted into a stable hydrate; 5) It is essential to remember that a small quantity of CO_2 leaking does not inevitably damage the sea bottom ecosystems.

Because of the anticipated development of dolomitic carbonate minerals, with the possibility of CO_2 being trapped in basalts for thousands of years, analysing changes in rock volume and the chance of fracture self-healing are key issues to consider. Quantitative research on such issues has been conducted (Van Pham et al., 2012). These researchers found out that at 40˚C, oxide consumed a significant amount of calcium, limiting its use to the creation of siderite and ferromagnesian carbonates. Magnesite formed with ankerite and siderite at temperatures between 60˚C and 100˚C. In addition, they found that the carbonation and hydration processes both increased solid volume and inhibited pore access, decreasing the maximum quantity of CO_2 stored.

In addition to studying the mineral assemblages present in basalt, researchers have looked at the mechanisms of mineral carbonation in serpentinites, intending to acquire a more thorough comprehension of the fundamentals of CO_2 storage for the future utilising basic magnesium silicates. In serpentinites, rocks that are both plentiful and thermodynamically suitable for the production of magnesium carbonates, CO_2 combines with magnesium silicates to produce magnesium carbonates (Seifritz 1990). Andreani et al. (2009) conducted an analysis of the carbonation process using flow parameters that were optimised. They found out that low-flow or low-diffusion regions are the only ones where porosity and permeability decrease. In contrast, higher flow rates contribute to armouring of mineral surfaces associated with the initial disintegration.

And further reason for alarm has been the occurrence of fractures in the basalt formations' protective cap-rock. Due to the possibility of leakage via the fissures, basalts are not likely to be suitable for CO_2 storage. However, CO_2 seeping via fissures has the potential to mineralize and be trapped inside the formation, delaying its escape to the surface (IEAGHG, 2011). As such, further research is required to characterise the kinetics of CO_2-basalt interactions.

Alternate storage alternatives, including serpentinite and basaltic reservoir formations, could be necessary; knowledge improvement is required to identify possible uncertainties and investigate mitigation techniques. To do so, it may be necessary to apply computational techniques and to research the impact of carbon dioxide and rock contact on the ease or difficulty of migration, as well as to clarify CO_2 migration in the presence of likely fault plane, fractures.

2.1.5. CO_2 Sequestration in Hydrate Deep Formations

Previous studies Yang et al., (2008) have shown that subsurface CO_2 storage systems as hydrates is another potential, modern strategy that uses a lattice of water molecules to capture CO_2 molecules. When water and the right level of pressure and temperature are present, CO_2 hydrate may form rapidly (Circone et al., 2003). Furthermore, its rapid formation kinetics may allow for some self-sealing in the rare crack development in the hydrate top layer formation. The development of CO_2 hydrate might have applications in both underground geology and the storage of CO_2 in the ocean. Because the formation of hydrate turns out to be very stable at higher pressure and low temperature of about 10˚C (Rochelle et al., 2009) they can only be used in certain situations, such as shallower sediments under cold oceans bed and under extensive areas of icy hydrate formation, where it's possible that there is a lack of sufficient space for a CO_2 collecting plant.

The process of CO_2 hydrate storage mechanism involves buoyancy and drives the migration of liquid CO_2, which is capped by a developing impermeable CO_2 hydrate cap (**Figure 4**). The CO_2 hydrate equilibrium zone is lowered by injecting liquid carbon dioxide into deep water or sub-permafrost sediments (Rochelle et al., 2009). As more liquid CO_2 moves into the colder hydrate stable zone, a layer of impenetrable CO_2-hydrates builds inside the pore holes of the sedimentary reservoir rock. The US Department of Energy (DOE) on the other hand proposed a CO_2-EGR-based hydrate storage technology (enhanced gas recovery). CO_2 is injected into sediments that contain methane hydrates, releasing the methane from the hydrates and forming CO_2 hydrates in its place (Burnol et al., 2015). Because CO_2-EGR is still a novel idea, research into its effectiveness has been limited so far. According to Oldenburg (2003), one of the primary issues is the use of Methane which might in turn react with the injected CO_2 in an enhanced gas cycle, resulting in the gas resources being depleted.

Presently, the technology required to store CO_2 in hydrates is not very advanced with most researchers (Jemai et al., 2014; Talaghat et al., 2009) focusing on theoretical modelling and lab-scale experiments (Ghavipour et al., 2013; Ruffine et al., 2010; Rehder et al., 2009). For this reason, there are still a number of challenges to be solved, especially with CO_2-EGR. However, local temperature and pressure fluctuations caused by drilling through hydrate-bearing

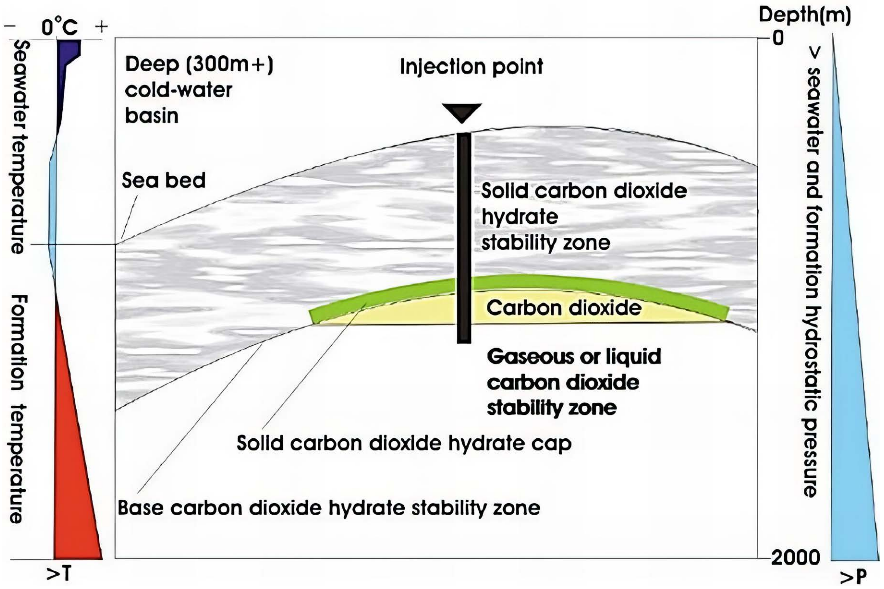


Figure 4. Illustration of hydrate formation diagram sequestration with its CO_2 Hydrate Seal (Rochelle et al., 2009).

sediments may destabilise the hydrate formation in its entirety (Khabibullin et al., 2011). How the CO_2-CH_4 hydrate exchange mechanism affects methane production, and how hydrate cap development may be shown as the major outstanding problems that need to be solved to improve the evaluation of hydrate storage viability.

2.1.6. Enhanced Geothermal Systems Based on CO_2

Previous studies (Garapati et al., 2015; Pruess, 2006; Song & Zhang, 2013) have emphasized that dense-phase CO_2, like water, has thermal characteristics that allow it to transfer large quantities of heat. However, it has better physical characteristics, such as substantially lower viscosity, more excellent compressibility, and expansibility. As a result, CO_2 may be utilised in the process of geothermal energy by extracting heat from the ground. CO_2 can efficiently reach the rock mass due to its low viscosity and may be considered a medium for enhanced geothermal systems' operating fluid (Pruess, 2006). Enhanced geothermal systems that use water as the heat transmission fluid experience drawback of fluid loss. The inability to provide adequate water supplies is associated with financial difficulties because of the value placed on this resource. On the other hand, if upgraded geothermal systems (EGS) were to lose their reliance on CO_2, this would make underground geological storage of CO_2 possible, which might have further benefits.

It is essential for the effectiveness of CO_2-EGS storage that the rock mass loaded with CO_2 be separated from the surrounding rock mass, which is filled with water. These conditions are maintained in large part due to the formation of crystals of carbonate minerals at the interface between the CO_2-heavy centre of EGS with the brine-rich outside. Only countries having subsurface resources at economically feasible depths where the temperature is high enough would be able to use this technology. Additionally, synergistic use of the subsurface may be more complicated and need more collaboration in heavily populated nations.

The technique is still in its early stages of technology readiness (TRL), with most research so far focused on theoretical modelling (Plaksina & White, 2016) and small-scale laboratory experiments. The main challenge to this method's development is the lack of clarity about the efficiency of closing off the area surrounding the CO_2 source. To top it all off, nothing is known about the interactions between CO_2 and rocks at high temperatures. Understanding how CO_2 affects dissolution and precipitation, and how that affects changes in fracture permeability and EGS functioning, requires further study

2.2. Carbonation of Mineral

Seifritz in 1990 was the first person to suggest the idea of CO_2 carbonation happening in the mineral as an alternative CO_2 sequestration method. The collected CO_2 is sequestered using this technique via the mineralisation process; in the presence of oxides or hydroxides of alkaline metals found in minerals, Carbonates are produced by the reaction of CO_2.

Incorporation of CO_2 into minerals may be accomplished in two ways: both in and out of place. The in-place technique includes injecting CO_2 into a geologic formation to produce carbonates. Meanwhile, the out-of-place process is carried out above the surface in a factory utilising rock that has been excavated earlier or rock that is indigenous to the area (Assima et al., 2014). In situ, mineral carbonation is often discussed in high-magnesium, high-iron, and high-calcium silicate rocks like basalts and ophiolites (Ekpo Johnson et al., 2023). The in-situ mineral carbonation technique has significant benefits since it does not need substantial mining and just a few boreholes to complete the process. However, there may be significant unknowns, such as the absence of geological characteristics or the lack of knowledge on the possible cap-rock or seal.

$$CO_2(g) + MgO(s) \rightarrow MgCO_3(s),\ \Delta H \approx -118\ KJ/mol$$

$$CO_2(g) + CaO(s) \rightarrow CaCO_3(s),\ \Delta H \approx -179\ KJ/mol$$

Also, geochemical processes may decrease reactivity, porosity, and permeability, lining the resultant flow channels. There are both direct and indirect techniques that could be used to carbonate minerals outside of their natural environments. The direct gas-based technique comprises the interaction of gaseous CO_2 with minerals to form carbonates, as previously shown (Bobicki et al., 2012). Gas-solid carbonation normally occurs at temperatures below 65˚C, with the rate of chemical reaction and the amount of space available in rocks being the key limiting variables (Calabrò et al., 2008). The direct aqueous-based process consists of a single stage, which entails CO_2 interacting with mineral deposits in the presence of water. This step takes place in the presence of water (Bobicki et al., 2012). Direct mineral carbonation has significant challenges in commercial deployment and development due to minerals and carbon dioxide being dissolved and forming a product layer dispersion (Olajire 2013; Bobicki et al., 2012). When looking at the feasibility of long-term mineral carbonation that allows for the underground sequestration of carbon dioxide, Matter and Kelemen in 2009 turned to natural analogues. According to their findings, sedimentary rocks that have magnesium and calcium elements in quite high concentrations tend to have a high rate of mineralization. Their results reveal that carbonate mineral precipitation may fill gaps already present, but that the tension caused by fast precipitation may also cause fracture and an increase in pore volume. The mining industry has a snowball impact on the environment because some mineral deposits that are rich in calcium and magnesium may also include asbestiform components as well as other pollutants that are harmful to human health (IPCC, 2005).

Two of the most common alkali and alkaline-earth metal oxides, magnesium oxide (MgO) and calcium oxide (CaO), don't develop as binary oxides in free existence. Magnesium oxide has the chemical formula MgO, while calcium oxide has the chemical formula CaO. Compounds based on silicon dioxide, such as serpentine, are typical examples of this kind of assemblage, Cipolli et al. (2004) and Bruni et al. (2002) conducted studies on the effects of carbon dioxide on serpentine that had been retrieved from the spring waters of Genova. Serpentinization modifies the complex interaction of ultramafic rocks with meteoric fluids, according to the results of a geochemical study of serpentinite-derived high-pH fluids and reaction-path simulation for aquifer-scale sequestration (Cipolli et al., 2004). $MgHCO_3$ waters are formed when CO_2 reacts with the rock, whereas Na-HCO^{3-} and Ca-OH type fluids are synthesised by further interactions with the host rock in a strongly lowering closed loop. Prior to employing reaction path modelling to simulate the process of injecting CO_2 at elevated pressure into aquifer formation, the findings suggested that serpentinites might be exploited for CO_2 sequestration because of their ability to create carbonate minerals. It should be emphasised that this method was only successful in reducing aquifer porosity under the circumstances of a closed system. This indicates that such consequences have to be examined thoroughly in both field and laboratory research.

Bruni and team in 2002 conducted research on the spring waters of the Genova area employing irreversible water-rock mass transfer. As a result of their investigation, they found some non-aligned Mg-HCO^3 fluids with several higher-pH Ca-OH fluids connected with serpentinites. They investigated if CO_2 sequestration is possible in the near and far future by dissolving serpentinite and then precipitating calcite. This was done in order to find out how effective this method might be. They determined that the interaction of these meteoric waters results in a gradual evolution in the chemistry of the aqueous phase. This development starts with magnesium-rich, low-salinity SO_4Cl facies and then moves on to intermediates facies made up of more developed Ca-OH and Mg-HCO^3 compounds. In order to arrive at this result, scientists examined dissolved N_2

and Ar in addition to water's stable isotopes. Higher alkalinity of Calcium Oxide solvent can capture CO_2 and transform it into deposits of Calcite formation or solute, this methodology might be used to sequester anthropogenic CO_2.

The implementation of a commercial process necessitates the extraction, pulverisation, and grinding of mineral-rich ores, as well as their transportation to a processing facility that receives a concentrated stream of CO_2 from a capture plant Figure 5. The energy consumption associated with the carbonation process is estimated to account for around 30% to 50% of the total output of the capture plant. When taking into account the supplementary energy demands associated with the capture of CO_2, it can be observed that a CCS system employing mineral carbonation necessitates an energy input per kilowatt-hour that is 60% to 180% higher compared to an electrical plant without capture or mineral carbonation, serving as a reference. The energy demands associated with this technology significantly increase the cost per metric tonne of CO_2 that is mitigated. The most exemplary case examined thus far pertains to the wet carbonation process of naturally occurring silicate olivine. The projected cost of this procedure is roughly 50 - 100 US$/t$CO_2$ net mineralized, accounting for CO_2 capture and transportation expenses, while also considering the supplementary energy demands.

The mineral carbonation process necessitates the extraction of about 1.6 to 3.7 tonnes of silicates per tonne of CO_2, and results in the disposal of 2.6 to 4.7 tonnes of materials per tonne of CO_2 stored as carbonates. Consequently, the

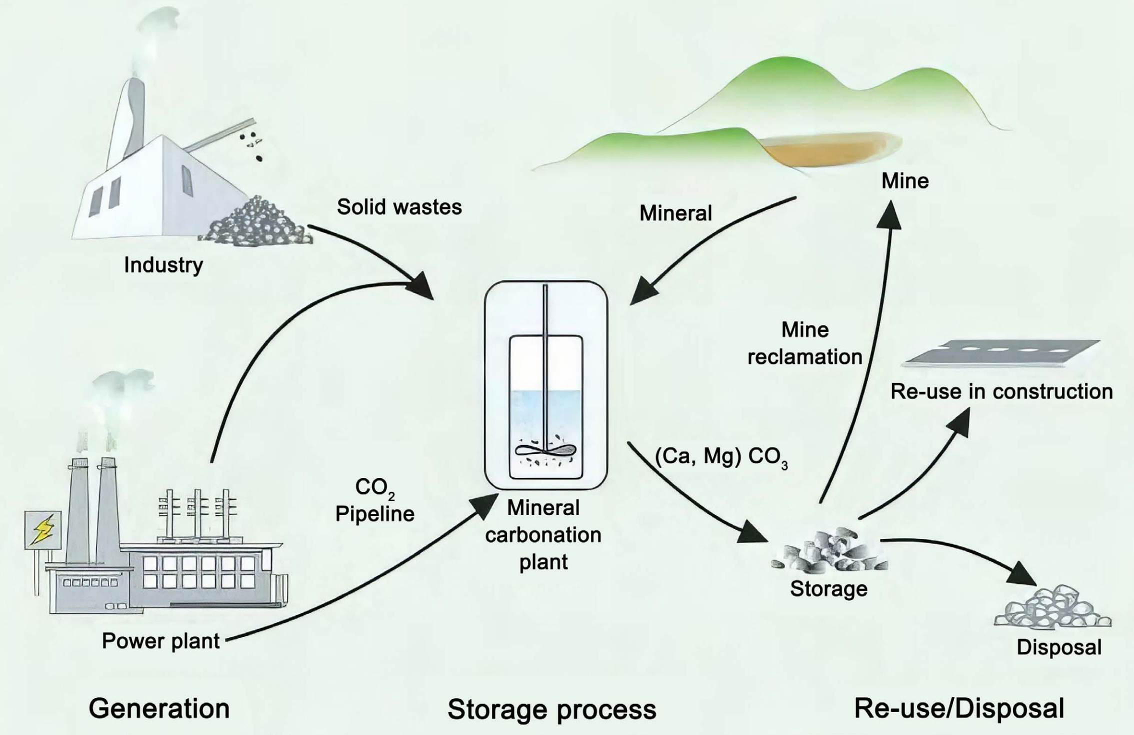


Figure 5. Illustrates the material fluxes and process processes that are involved in the mineral carbonation of silicate rocks or industrial residues (Huijgen et al., 2005).

proposed endeavour would constitute a substantial undertaking, with an environmental footprint akin to that of existing extensive surface mining operations. Serpentine is frequently found to contain chrysotile, which is a naturally occurring variant of asbestos.

The existence of this phenomenon necessitates the implementation of monitoring and mitigation strategies similar to those utilised in the mining sector. In contrast, the by-products of mineral carbonation do not contain chrysotile, as it is the most reactive constituent of the rock and hence undergoes conversion to carbonates at the earliest stage.

Limitation and Future Work

There are several unresolved concerns that must be addressed before any assessments of the storage capacity of mineral carbonation can be provided. The concerns encompass evaluations of the technological feasibility and associated energy demands on a significant scale, as well as the proportion of silicate deposits that may be viably and economically utilised for CO_2 storage. The potential of mining, waste disposal, and product storage may be limited due to their environmental impact. The current feasibility of utilising mineral carbonation remains uncertain due to the lack of knowledge regarding the potential quantity of exploitable silicate reserves and the presence of environmental concerns, as previously mentioned.

Another crucial inquiry is to the potential of industrial utilisation of CO_2 to yield a net decrease in CO_2 emissions on a comprehensive scale, through the substitution of alternative industrial processes or products. Accurate evaluation of the CO_2 utilisation processes necessitates the consideration of appropriate system boundaries for energy and material balances, as well as the execution of a comprehensive life-cycle study pertaining to the intended utilisation of CO_2. The existing body of literature pertaining to this subject is constrained in scope, although it reveals the challenges associated with accurately quantifying specific data. Moreover, it suggests that in numerous instances, the utilisation of industrial practices may result in an overall rise in emissions rather than a net decrease. Based on the limited amount of CO_2 kept, the modest quantities utilised, and the potential for substitution resulting in elevated CO_2 emissions, it may be deduced that the impact of industrial applications of captured CO_2 on mitigating climate change is anticipated to be minimal. Currently, there has been limited effort in evaluating and quantifying the aforementioned external costs. The examination of CCS is conducted within the framework of exploring various strategies for achieving worldwide reductions in greenhouse gas emissions.

Likewise, mineral carbonation might cause issues for both humans and the environment. Mineral carbonation processes have the potential to change the topography of an area in two different ways: via large-scale mining activities and, later on, through the disposal of reacted minerals. In addition, asbestiform phases and other potentially harmful pollutants may be present in some calcium and magnesium-rich mineral formations (IPCC, 2005). Accordingly, future research should concentrate on 1) The potential for less terrain change; 2) Mineral carbonation in terms of mineral and CO_2 dissolution; 3) Material stratum diffusion; and 4) Managing mineral impurities throughout the sequestration process.

2.3. CO_2 Sequestration on Ocean Floor

Intentionally injecting CO_2 into the deep ocean floor is another option for anthropogenic CO_2 sequestration (IPCC, 2018). The oceans cover around 70% of the planet. In the industrial era, they sucked up over a third of all man-made CO_2 emissions from the atmosphere and had an average depth of 3.8 km (Tanhua et al., 2015). Mathematical simulations have indicated that injected CO_2 may linger in the water for hundreds of years. This cold (1˚C) and profound (4 to 5 km) water flows slowly and may stay isolated from the atmosphere for millennia.

There are two potential methods for ocean storage: the injection and dissolution of CO_2 into the water column, typically below 1000 metres, using a fixed pipeline or a floating ship; or the deposition of CO_2 onto the sea floor at depths below 3000 metres, using a fixed pipeline or an offshore platform. In the latter method, CO_2, being denser than water, is expected to form a concentrated "lake" that would delay its dissolution into the surrounding environment (**Figure 6**. below). The investigation of ocean storage and its ecological consequences is currently in the research phase.

The process of ocean storage can be classified into two types: dissolution type

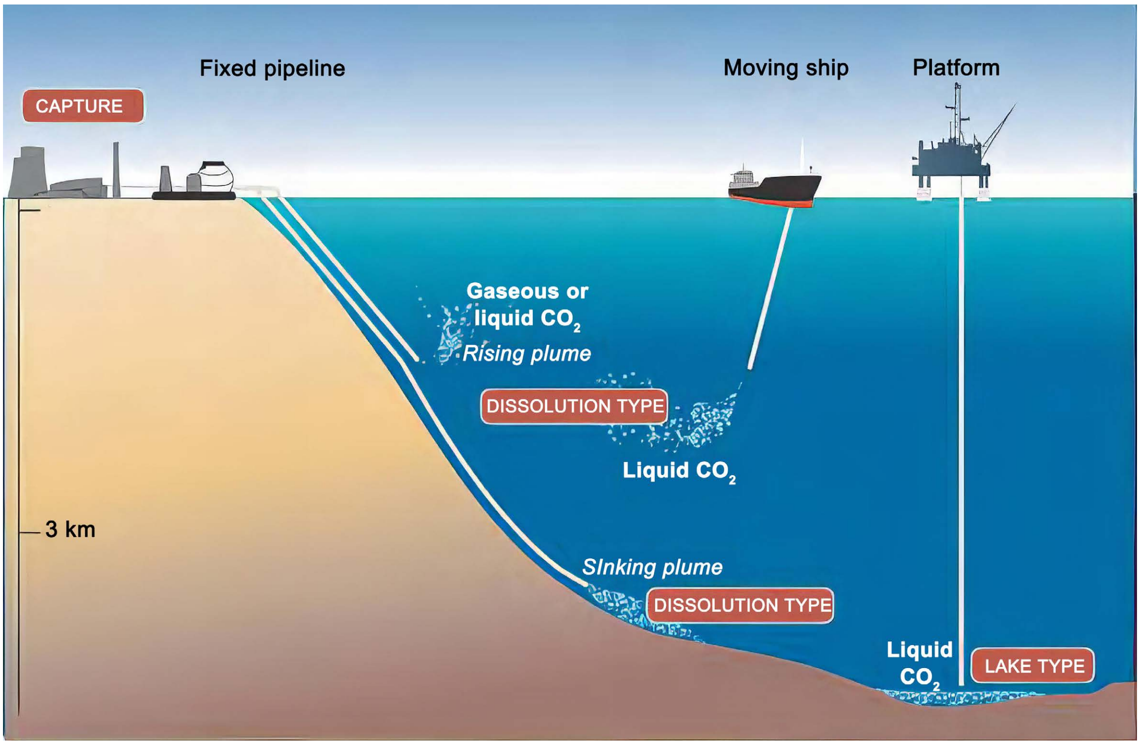


Figure 6. An illustration of many concepts related to the storage of CO_2 in the ocean.

and lake type. In the dissolution type, CO_2 undergoes rapid dissolution in ocean water. On the other hand, in the lake type, CO_2 exists initially as a liquid on the sea floor (CO_2CRC).

Direct CO_2 dissolution into seawater is the principal technique that could be used in ocean storage. The first involves releasing CO_2 directly into the ocean floor, where it will form droplet plumes that will rise into the air. As an alternate method, liquid CO_2 is injected into a column, where it has the potential to interact with saltwater at a pace that is under control, therefore producing hydrate (Adams et al., 2008). Since there is a potential for localised acidification of water from the sea in the vicinity of CO_2 injection location, the storage of CO_2 on the ocean floor is viewed with scepticism by a number of experts. This would have a deleterious effect on the benthic organisms. This is according to a series of recent studies published by Jacobson in 2009 and (Hofmann & Schellnhuber, 2010). Furthermore, it is unclear if international laws will permit CO_2 storage in the ocean as a development project. The London Convention for the Protection of the Marine Environment from Pollution by Dumping of Wastes and Other Matter into the Sea signed in 1996 put an end to the practice of discharging wastes from industrial processes into the ocean (Nobre et al., 1991; Szizybalski et al., 2014). Therefore, it is prohibited to dump CO_2 into the ocean if it is considered industrial waste. Although CO_2 was added to the "reverse list" in the London Protocol modification that allowed for the storage of CO_2 beneath the seabed in 2006, there is still no agreement on whether or not CO_2 should be classified as industrial waste. "CO_2 may only be stored in compliance with an authorisation or permit given by the Party's competent authority," as stated in the North-East Atlantic Convention with the Interest of Preserving the Quality of the Marine Environment (DePaolo et al., 2013; ZeroCO_2 2015). Therefore, it is necessary to evaluate the ambiguity surrounding ocean sequestration and its effects on the ecosystem and to provide solutions to possible problems that may arise.

Oceanic sequestration efficiency may be evaluated based on a number of criteria, the most important of which are injection depth, residence time, and CO_2 concentration allocation. Xu et al. (1999) constructed a regional ocean general circulation model that assumed there was no air-to-sea CO_2 exchange and investigated the prospect for CO_2 sequestration in the North Pacific by using a wide range of sub-grid mesoscale mixing parameters. According to their findings, storage depth is a crucial factor in sequestering CO_2 and limiting its emissions back into the atmosphere. It was discovered that a depth of injection of more than 1000 metres is necessary to slowly release CO_2 into the water over very few 100 years.

Following fifty years of constant injection of CO_2, more than ten percent of the dissolved CO_2 would be released back into the environment. This leakage should be considered as a major concern. Adcroft et al., in 2004 used an ocean circulation model to assess the storage efficiency of impulse injections based on mean residence time. CO_2 sequestration was more successful in the North Atlantic over hundreds of years, whereas it was more successful in the Pacific basin over shorter periods. Although the magnitudes that were tested were low and that the impact of air-sea CO_2 circulation was ignored, the relevance of this effect over large borders is still a concern and calls for more research.

In order to assess the efficacy of a potential sequestration location, the variation in CO_2 concentration after injection might be considered. A place where CO_2 is adequately diluted while having little environmental impact is preferable. However, by simulating CO_2 injection into a number of models of the ocean's main circulation at several sites around Japan, the spatial variability of CO_2 content concerning injection rate and eddy activity distribution has been studied (Masuda et al., 2009). These researchers used an ocean general circulation model to perform their research. Specifically, the data indicated that the highest CO_2 concentration may vary by a factor of 10 across places, where the principal driver of this variation is the regionalization of turbulent events. Additionally, it has been established that keeping injection rates below 20 Mt/a would have little long-term impact on biota.

Limitation and Future Work

In order to advance the discussions surrounding the evaluation of oceanic sequestration, previous study has shown that a number of improvements and unknowns need to be investigated and resolved in future studies. One way to boost ocean storage efficiency is by updating the present numerical model to account for CO_2 exchange between the atmosphere and the ocean, and second, by reducing the number of assumptions underlying the model, further investigating the determination of storage efficiency.

The advancement of ocean CSS can be facilitated by addressing many significant gaps in knowledge and understanding, some of these gaps thus include: 1) Further engineering and advancement of technology for operating in the deep sea, as well as the development of various equipment such as pipes, nozzles, and diffusers, that can be efficiently utilised in deep-sea environments while ensuring minimal costs for operation and maintenance; 2) Biological and ecological factors – Investigations pertaining to the impact of increased CO_2 levels on biological systems inside the deep sea, encompassing investigations of greater duration and larger size than those previously conducted; 3) Research centres – these are establishments dedicated to conducting scientific research and developing technologies related to ocean storage. They provide a platform for assessing the effectiveness and impacts of various ocean storage concepts, such as the release of CO_2 from a fixed pipe or ship, as well as carbonate-neutralization approaches. These assessments are carried out in situ, on a small scale, and an ongoing basis; 4) Finally, the future focus should be on the advancement of methodologies and sensor technologies to detect CO_2 plumes, as well as understanding their ecological and geochemical impacts.

3. Discussion and Conclusions

This paper provides a comprehensive review of the current advancements in

CO_2 sequestration with special interest in geological CO_2 storage. This highlights significant steps that have been covered so far, as well as obstacles that still need to be addressed for geological subsurface CO_2 sequestration, and approaches adopted in calculating CO_2 storage capacity.

Even though CO_2 sequestration by storage in the ocean and storage through the process of carbonation has been established, CSS remains the most viable option practical alternative because of financial concerns, vast geographical dispersal, and environmental difficulties. This is the case because it has been proven that CO_2 can be sequestered.

Mineral CO_2 sequestration on the other hand remains a more protracted alternative in comparison to other potential carbon sequestration methods. The current state of technological progress restricts the short-term sequestration potential. In addition, the present costs associated with its sequestration are somewhat excessive when compared to alternative sequestration methods, taking into account the projected prices of CO_2 in the near future. Feasibility may be limited to specific uses that offer an extra benefit, such as the practical utilisation of the carbonated product. Mineral CO_2 sequestration has the potential to evolve into a viable technology for employment, forming an integral component of a diverse range of CO_2-reducing technologies. It is crucial to use each technology in its most suitable context within a comprehensive portfolio. The field of mineral CO_2 sequestration is a relatively recent area of study, and significant advancements have been achieved in improving the pace at which carbonation occurs. The aforementioned observation, in conjunction with the enduring nature of CO_2 sequestration and its substantial potential for sequestration, justifies the need for additional investigation into mineral CO_2 sequestration.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. This work is an outcome of research work in the Chemical Engineering Program, School of Engineering, Faculty of Engineering and Digital Technologies, University of Bradford.

Conflicts of Interest

Authors declare that they do not have any conflict of interest with anyone regarding this article.

References

Adams, R. A., & Hayes, M. A. (2008). Water Availability and Successful Lactation by Bats as Related to Climate Change in Arid Regions of Western North America. *Journal of Animal Ecology, 77,* 1115-1121. https://doi.org/10.1111/j.1365-2656.2008.01447.x

Andreani, M., Luquot, L., Gouze, P., Godard, M., Hoisé, E., & Gibert, B. (2009). Experimental Study of Carbon Sequestration Reactions Controlled by the Percolation of CO_2-Rich Brine through Peridotites. *Environmental Science & Technology, 43,* 1226-1231. https://doi.org/10.1021/es8018429

Anthonsen, K. L., Aagaard, P., Bergmo, P. E. S., Gislason, S. R., Lothe, A. E., Mortensen, G. M., & Snæbjörnsdóttir, S. (2014). Characterisation and Selection of the Most Prospective CO_2 Storage Sites in the Nordic Region. *Energy Procedia, 63,* 4884-4896. https://doi.org/10.1016/j.egypro.2014.11.519

Armitage, P. J., Worden, R. H., Faulkner, D. R., Aplin, A. C., Butcher, A. R., & Espie, A. A. (2013). Mercia Mudstone Formation Caprock to Carbon Capture and Storage Sites: Petrology and Petrophysical Characteristics. *Journal of the Geological Society of London, 170,* 119-132. https://doi.org/10.1144/jgs2012-049

Assima, G. P., Larachi, F., Molson, J., & Beaudoin, G. (2014). Impact of Temperature and Oxygen Availability on the Dynamics of Ambient CO_2 Mineral Sequestration by Nickel Mining Residues. *Chemical Engineering Journal, 240,* 394-403. https://doi.org/10.1016/j.cej.2013.12.010

Bachu, S. (2003). Screening and Ranking of Sedimentary Basins for Sequestration of CO_2 in Geological Media in Response to Climate Change. *Environmental Geology, 44,* 277-289. https://doi.org/10.1007/s00254-003-0762-9

Bachu, S. (2010). Screening and Selection Criteria, and Characterisation Techniques for the Geological Sequestration of Carbon Dioxide (CO_2). In M. M. Maroto-Valer (Ed.), *Developments and Innovation in Carbon Dioxide (CO_2) Capture and Storage Technology* (pp. 27-56). Woodhead Publishing. https://doi.org/10.1533/9781845699581.1.27

Bachu, S. (2015). Review of CO_2 Storage Efficiency in Deep Saline Aquifers. *International Journal of Greenhouse Gas Control, 40,* 188-202. https://doi.org/10.1016/j.ijggc.2015.01.007

Bachu, S., & Rothenburg, L. (1998). Carbon Dioxide Sequestration in Salt Caverns: Capacity and Long Term Fate. *Journal of Canadian Petroleum Technology.*

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N. P., & Mathiassen, O. M. (2007). CO_2 Storage Capacity Estimation: Methodology and Gaps. *International Journal of Greenhouse Gas Control, 1,* 430-443. https://doi.org/10.1016/S1750-5836(07)00086-2

Bachu, S., Brulotte, M., Grobe, M. et al. (2000). *Suitability of the Alberta Subsurface for Carbon Dioxide Sequestration in Geological Media.*

Bai, X., van der Leeuw, S., O'Brien, K., Berkhout, F., Biermann, F., Brondizio, E. S., Cudennec, C., Dearing, J., Duraiappah, A., Glaser, M., Revkin, A., Steffen, W., & Syvitski, J. (2015). Plausible and Desirable Futures in the Anthropocene: A New Research Agenda. *Global Environmental Change, 39,* 351-362. https://doi.org/10.1016/j.gloenvcha.2015.09.017

BGS (2017). *Man-Made (Anthropogenic) Greenhouse Gases.* https://www.bgs.ac.uk/discovering-geology/climate-change/CCS/Anthropogenic.html

Bobicki, E. R., Liu, Q., Xu, Z., & Zeng, H. (2012). Carbon Capture and Storage Using Alkaline Industrial Wastes. *Progress in Energy and Combustion Science, 38,* 302-320. https://doi.org/10.1016/j.pecs.2011.11.002

Bruni, J., Canepa, M., Chiodini, G., Cioni, R., Cipolli, F., Longinelli, A. et al. (2002). Irreversible Water-Rock Mass Transfer Accompanying the Generation of the Neutral, Mg-HCO_3 and High-pH, Ca-OH Spring Waters of the Genova Province, Italy. *Applied Geochemistry, 17,* 455-474. https://doi.org/10.1016/S0883-2927(01)00113-5

Burnol, A., Thinon, I., Ruffine, L., & Herri, J. M. (2015). Influence of Impurities (Nitrogen and Methane) on the CO_2 Storage capacity As Sediment-Hosted Gas Hydrates—Application in the Area of the Celtic Sea and the Bay of Biscay. *International Journal of Greenhouse Gas Control, 35,* 96-109. https://doi.org/10.1016/j.ijggc.2015.01.018

Buttinelli, M., Procesi, M., Cantucci, B., Quattrocchi, F., & Boschi, E. (2011). The Geo-Database of Caprock Quality and Deep Saline Aquifers Distribution for Geological Storage of CO_2 in Italy. *Energy, 36,* 2968-2983. https://doi.org/10.1016/j.energy.2011.02.041

Calabrò, A., Deiana, P., Fiorini, P., Girardi, G., & Stendardo, S. (2008). Possible Optimal Configurations for the ZECOMIX High Efficiency Zero Emission Hydrogen and Power Plant. *Energy, 33,* 952-962. https://doi.org/10.1016/j.energy.2008.01.004

Cantucci, B., Montegrossi, G., Vaselli, O., Tassi, F., Quattrocchi, F., & Perkins, E. H. (2009). Geochemical Modeling of CO_2 Storage in Deep Reservoirs: The Weyburn Project (Canada) Case Study. *Chemical Geology, 265,* 181-197. https://doi.org/10.1016/j.chemgeo.2008.12.029

Cipolli, F., Gambardella, B., Marini, L., Ottonello, G., & Zuccolini, M. V. (2004). Geo-Chemistry of High-pH Waters from Serpentinites of the Gruppo di Voltri (Genova, Italy) and Reaction Path Modeling of CO_2 Sequestration in Serpentinite Aquifers. *Applied Geochemistry, 19,* 787-802. https://doi.org/10.1016/j.apgeochem.2003.10.007

Circone, S., Stern, L. A., Kirby, S. H., Durham, W. B., Chakoumakos, B. C., Rawn, C. J. et al. (2003). CO_2 Hydrate: Synthesis, Composition, Structure, Dissociation Behavior, and a Comparison to Structure I CH_4 Hydrate. *The Journal of Physical Chemistry B, 107,* 5529-5539. https://doi.org/10.1021/jp027391j

CO_2CRC (2015). *CO_2 Dispersion*. Cooperative Research Centre for Greenhouse Gas Technologies.

DECC (2012). *CCS Roadmap—Supporting deployment of Carbon Capture and Storage in the UK.*

DePaolo, D. J., Cole, D. R., Navrotsky, A., & Bourg, I. C. (2013). *Geochemistry of Geologic CO_2 Sequestration*. De Gruyter. https://doi.org/10.1515/9781501508073

ECF (2010). *Roadmap 2050: A Practical Guide to a Prosperous, Low-Carbon Europe.*

Ekpo Johnson, E., Scherwath, M., Moran, K., Dosso, S. E., & Rohr, K. M. (2023). Fault Slip Tendency Analysis for a Deep-Sea Basalt CO_2 Injection in the Cascadia Basin. *GeoHazards, 4,* 121-135. https://doi.org/10.3390/geohazards4020008

Fleury, M., Pironon, J., Le Nindre, Y. M., Bildstein, O., Berne, P., Lagneau, V. et al. (2010). Evaluating Sealing Efficiency of Caprocks for CO_2 Storage: An Overview of the Geocarbone-Integrity Program and Results. *Oil & Gas Science and Technology, 65,* 435-444. https://doi.org/10.2516/ogst/2010007

Frerichs, J., Rakoczy, J., Ostertag-Henning, C., & Krüger, M. (2014). Viability and Adaptation Potential of Indigenous Microorganisms from Natural Gas Field Fluids in High Pressure Incubations with Supercritical CO_2. *Environmental Science & Technology, 48,* 1306-1314. https://doi.org/10.1021/es4027985

Gao, R. S., Sun, A. Y., & Nicot, J. P. (2016). Identification of a Representative Dataset for Long-Term Monitoring at the Weyburn CO_2-Injection Enhanced Oil Recovery Site, Saskatchewan, Canada. *International Journal of Greenhouse Gas Control, 54,* 454-465. https://doi.org/10.1016/j.ijggc.2016.05.028

Garapati, N., Randolph, J. B., & Saar, M. O. (2015). Brine Displacement by CO_2, Energy Extraction Rates, and Lifespan of a CO_2-Limited CO_2-Plume Geothermal (CPG) System with a Horizontal Production Well. *Geothermics, 55,* 182-194. https://doi.org/10.1016/j.geothermics.2015.02.005

GCCSI (2011). *Accelerating the Uptake of CCS: Industrial Use of Captured Carbon Dioxide.*

GCCSI (2017). *Alberta Carbon Trunk Line ("ACTL") with North West Sturgeon Refinery*

CO_2 Stream. Global CCS Institute. https://co2re.co/FacilityData

Ghavipour, M., Ghavipour, M., Chitsazan, M., Najibi, S. H., & Ghidary, S. S. (2013). Experimental Study of Natural Gas Hydrates and a Novel Use of Neural Network to Predict Hydrate Formation Conditions. *Chemical Engineering Research and Design, 91,* 264-273. https://doi.org/10.1016/j.cherd.2012.08.010

Gilliland, E. S., Ripepi, N., Conrad, M., Miller, M. J., & Karmis, M. (2013). Selection of Monitoring Techniques for a Carbon Storage and Enhanced Coalbed Methane Recovery Pilot Test in the Central Appalachian Basin. *International Journal of Coal Geology, 118,* 105-112. https://doi.org/10.1016/j.coal.2013.07.007

Gilliland, E., Ripepi, N., Karmis, M., & Conrad, M. (2012). An Examination of MVA Techniques Applicable for CCUS in Thin, Stacked Coals of the Central Appalachian Basin. *29th Annual International Pittsburgh Coal Conference 2012, 3,* 1931-1938.

Gunter, W. D., Bachu, S., & Benson, S. (2004). The Role of Hydrogeological and Geochemical Trapping in Sedimentary Basins for Secure Geological Storage of Carbon Dioxide. *Geological Society London, 233,* 129-145. https://doi.org/10.1144/GSL.SP.2004.233.01.09

Han, Y., & Winston Ho, W. S. (2020). Recent Advances in Polymeric Facilitated Transport Membranes for Carbon Dioxide Separation and Hydrogen Purification. *Journal of Polymer Science, 58,* 2435-2449. https://doi.org/10.1002/pol.20200187

Hanak, D. P., Anthony, E. J., & Manovic, V. (2015). A Review of Developments in Pilot-Plant Testing and Modelling of Calcium Looping Process for CO_2 Capture from Power Generation Systems. *Energy & Environmental Science, 8,* 2199-2249. https://doi.org/10.1039/C5EE01228G

Heinemann, N., Stewart, R. J., Wilkinson, M., Pickup, G. E., & Haszeldine, R. S. (2016). Hydrodynamics in Subsurface CO_2 Storage: Tilted Contacts and Increased Storage Security. *International Journal of Greenhouse Gas Control, 54,* 322-329. https://doi.org/10.1016/j.ijggc.2016.10.003

Hofmann, M., & Schellnhuber, H. J. (2010). Ocean Acidification: A Millennial Challenge. *Energy & Environmental Science, 3,* 1883-1896. https://doi.org/10.1039/c000820f

Huijgen, W., Witkamp, G., & Comans, R. (2005). *Carbon Dioxide Sequestration by Mineral Carbonation*. Energy Research Centre of the Netherlands (ECN).

Hutcheon, I., Shevalier, M., Durocher, K., Bloch, J., Johnson, G., Nightingale, M., & Mayer, B. (2016). Interactions of CO_2 with Formation Waters, Oil and Minerals and CO_2 Storage at the Weyburn IEA EOR Site, Saskatchewan, Canada. *International Journal of Greenhouse Gas Control, 53,* 354-370. https://doi.org/10.1016/j.ijggc.2016.08.004

IEAGHG (2009a). *CO_2 Storage in Depleted Gas Fields.*

IEAGHG (2009b). *Long Term Integrity of CO_2 Storage—Well Abandonment.*

IEAGHG (2011). *Effects of Impurities on Geological Storage of CO_2.* Cheltenham.

Igunnu, E. T., & Chen, G. Z. (2014). Produced Water Treatment Technologies. *International Journal of Low-Carbon Technologies, 9,* 157-177. https://doi.org/10.1093/ijlct/cts049

International Energy Agency (IEA) (2015). *Storing CO_2 through Enhanced Oil Recovery, Combining EOR with CO_2 Storage (EOR) for Profit.*

IPCC (2005). *Special Report on Carbon Dioxide Capture and Storage.*

IPCC (2018). *Special Report on Global Warming, Summary for Policymakers.*

Jaramillo, P., Griffin, W. M., & Matthews, H. S. (2008). Comparative Analysis of the Production Costs and Life-Cycle GHG Emissions of FT Liquid Fuels from Coal and

Natural Gas. *Environmental Science & Technology, 42,* 7559-7565. https://doi.org/10.1021/es8002074

Jarrell, P. M., Fox, C. E., Stein, M. H., & Webb, S. L. (2002). *Practical Aspects of CO_2 Flooding*. SPE Monograph Series No. 22, 220 p. https://doi.org/10.2118/9781555630966

Javaheri, M., & Jessen, K. (2011). Residual Trapping in Simultaneous Injection of CO_2 and Brine in Saline Aquifers. In *SPE Western North America and Rocky Mountain Joint Regional Meeting* (p. 603). Society of Petroleum Engineers. https://doi.org/10.2118/144613-MS

Jemai, K., Kvamme, B., & Vafaei, M. T. (2014). Theoretical Studies of CO_2 Hydrates Formation and Dissociation in Cold Aquifers Using RetrasoCodeBright Simulator. *WSEAS Transactions on Heat and Mass Transfer, 9,* 150-168.

Khabibullin, T., Falcone, G., & Teodoriu, C. (2011). Drilling through Gas-Hydrate Sediments: Managing Wellbore-Stability Risks. *SPE Drilling & Completion, 26,* 287-294. https://doi.org/10.2118/131332-PA

Kim, Y., Jang, H., Kim, J., & Lee, J. (2017). Prediction of Storage Efficiency on CO_2 Sequestration in Deep Saline Aquifers Using Artificial Neural Network. *Applied Energy, 185,* 916-928. https://doi.org/10.1016/j.apenergy.2016.10.012

Kneafsey, T. J., & Pruess, K. (2010). Laboratory Flow Experiments for Visualizing Carbon Dioxide-Induced, Density-Driven Brine Convection. *Transport in Porous Media, 82,* 123-139. https://doi.org/10.1007/s11242-009-9482-2

Krooss, B. M., Van Bergen, F., Gensterblum, Y., Siemons, N., Pagnier, H. J. M., & David, P. (2002). High-Pressure Methane and Carbon Dioxide Adsorption on Dry and Moisture-Equilibrated Pennsylvanian Coals. *International Journal of Coal Geology, 51,* 69-92. https://doi.org/10.1016/S0166-5162(02)00078-2

Kuuskraa, V., & Ferguson, R. (2008). *Storing CO_2 with Enhanced Oil Recovery*. National Energy Technology Laboratory.

Lakeman, B. (2016). *Alberta Research Council Enhanced Coalbed Methane Recovery Project in Alberta, Canada*. Alberta Research Council (ARC) Inc.

Le Gallo, Y., Couillens, P., & Manai, T. (2002). CO_2 Sequestration in Depleted Oil or Gas Reservoirs. In *International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production* (pp. 1390-1392). Society of Petroleum Engineers. https://doi.org/10.2118/74104-MS

Li, Q., Wei, Y. N., Liu, G., & Lin, Q. (2014). Combination of CO_2 Geological Storage with Deep Saline Water Recovery in Western China: Insights from Numerical Analyses. *Applied Energy, 116,* 101-110. https://doi.org/10.1016/j.apenergy.2013.11.050

Li, S., Wang, P., & Wang, Z. (2023). Strategy to Enhance Geological CO_2 Storage Capacity in Saline Aquifer. *Geophysical Research Letters, 50,* e2022GL101431. https://doi.org/10.1029/2022GL101431

Mabon, L., & Shackley, S. (2013). Public Engagement in Discussing Carbon Capture and Storage. In *World Social Science Report 2013—Changing Global Environments* (pp. 398-403). ISSC, UNESCO. https://doi.org/10.1787/9789264203419-71-en

MacDowell, N., Florin, N., Buchard, A., Hallett, J., Galindo, A., Jackson, G. et al. (2013). An Overview of CO_2 Capture Technologies. *Energy & Environmental Science, 3,* 1645-1669. https://doi.org/10.1039/c004106h

Marston, P. (2013). *Bridging the Gap: An Analysis and Comparison of Legal and Regulatory Frameworks for CO_2-EOR and CO_2-CCS*. Global CCS Institute.

Masuda, Y., Yamanaka, Y., Sasai, Y., Magi, M., & Ohsumi, T. (2009). Site Selection in CO_2 Ocean Sequestration: Dependence of CO_2 Injection Rate on Eddy Activity Distribution.

International Journal of Greenhouse Gas Control, 3, 67-76. https://doi.org/10.1016/j.ijggc.2008.07.002

Matter, J. M., Broecker, W. S., Gislason, S. R., Gunnlaugsson, E., Oelkers, E. H., Stute, M. et al. (2011). The CarbFix Pilot Project—Storing Carbon Dioxide in Basalt. *Energy Procedia, 4,* 5579-5585. https://doi.org/10.1016/j.egypro.2011.02.546

Matter, J. M., Stute, M., Snæbjörnsdottir, S. Ó., Oelkers, E. H., Gislason, S. R., Aradottir, E. S. et al. (2016). Rapid Carbon Mineralization for Permanent Disposal of Anthropogenic Carbon Dioxide Emissions. *Science, 352,* 1312-1314. https://doi.org/10.1126/science.aad8132

McGrail, B. P., Schaef, H. T., Ho, A. M., Chien, Y.-J., Dooley, J. J., & Davidson, C. L. (2006). Potential for Carbon Dioxide Sequestration in Flood Basalts. *Journal of Geophysical Research: Solid Earth, 111.* https://doi.org/10.1029/2005JB004169

MIT (2015). *Carbon Capture and Sequestration Technologies.* Massachusetts Institute of Technology. https://sequestration.mit.edu/tools/projects/index.html

Na, J., Xu, T., Yuan, Y., Feng, B., Tian, H., & Bao, X. (2015). An Integrated Study of Fluid-Rock Interaction in a CO_2-Based Enhanced Geothermal System: A Case Study of Songliao Basin, China. *Applied Geochemistry, 59,* 166-177. https://doi.org/10.1016/j.apgeochem.2015.04.018

Nobre, C. A., Sellers, P. J., & Shukla, J. (1991). Amazonian Deforestation and Regional Climate Change. *Journal of Climate, 4,* 957-988. https://www.jstor.org/stable/26196408?saml_data=eyJzYW1sVG9rZW4iOiJjNGVkZDY0OC1kOTNlLTQxZWMtODE0ZS04M2NhMzA3ZjJhYjIiLCJpbnN0aXR1dGlvbklkcyI6WyI1ZjhlMTUzZS02MzI1LTQ5NTgtOWRmZC0xOTBjNjg1YjE0MDQiXX0#metadata_info_tab_contents

Olajire, A. A. (2013). A Review of Mineral Carbonation Technology in Sequestration of CO_2. *Journal of Petroleum Science and Engineering, 109,* 364-392. https://doi.org/10.1016/j.petrol.2013.03.013

Oldenburg, C. M. (2003). *Carbon Sequestration in Natural Gas Reservoirs: Enhanced Gas Recovery and Natural Gas Storage.* Lawrence Berkeley National Laboratory.

Perera, M. S. A., Gamage, R. P., Rathnaweera, T. D., Ranathunga, A. S., Koay, A., & Choi, X. A. (2016). Review of CO_2-Enhanced Oil Recovery with a Simulated Sensitivity Analysis. *Energies, 9,* Article 481. https://doi.org/10.3390/en9070481

Plaksina, T., & White, C. (2016). Modeling Coupled Convection and Carbon Dioxide Injection for Improved Heat Harvesting in Geopressured Geothermal Reservoirs. *Geothermal Energy, 4,* Article No. 2. https://doi.org/10.1186/s40517-016-0044-x

Pollyea, R. M., Fairley, J. P., Podgorney, R. K., & Mcling, T. L. (2014). Physical Constraints on Geologic CO_2 Sequestration in Low-Volume Basalt Formations. *Bulletin of the Geological Society of America, 126,* 344-351. https://doi.org/10.1130/B30874.1

Porter, R. T. J., Fairweather, M., Pourkashanian, M., & Woolley, R. M. (2015). The Range and Level of Impurities in CO_2 Streams from Different Carbon Capture Sources. *International Journal of Greenhouse Gas Control, 36,* 161-174. https://doi.org/10.1016/j.ijggc.2015.02.016

Procesi, M., Cantucci, B., Buttinelli, M., Armezzani, G., Quattrocchi, F., & Boschi, E. (2013). Strategic Use of the Underground in an Energy Mix Plan: Synergies among CO_2, CH_4 Geological Storage and Geothermal Energy. Latium Region Case Study (Central Italy). *Applied Energy, 110,* 104-131. https://doi.org/10.1016/j.apenergy.2013.03.071

Pruess, K. (2006). Enhanced Geothermal Systems (EGS) Using CO_2 as Working Fluid—A Novel Approach for Generating Renewable Energy with Simultaneous Sequestration of

Carbon. *Geothermics, 35,* 351-367. https://doi.org/10.1016/j.geothermics.2006.08.002

Quattrocchi, F., Boschi, E., Spena, A., Buttinelli, M., Cantucci, B., & Procesi, M. (2013). Synergic and Conflicting Issues in Planning Underground Use to Produce Energy in Densely Populated Countries, as Italy. Geological Storage of CO_2, Natural Gas, Geothermics and Nuclear Waste Disposal. *Applied Energy, 101,* 393-412. https://doi.org/10.1016/j.apenergy.2012.04.028

Rehder, G., Leifer, I., Brewer, P. G., Friederich, G., & Peltzer, E. T. (2009). Controls on Methane Bubble Dissolution inside and outside the Hydrate Stability Field from Open Ocean Field Experiments and Numerical Modeling. *Marine Chemistry, 114,* 19-30. https://doi.org/10.1016/j.marchem.2009.03.004

Rochelle, C. A., Camps, A. P., Long, D., Milodowski, A., Bateman, K., Gunn, D., Jackson, P., Lovell, M. A., & Rees, J. (2009). Can CO_2 Hydrate Assist in the Underground Storage of Carbon Dioxide? *Geological Society Special Publication, 319,* 171-183. https://doi.org/10.1144/SP319.14

Ruffine, L., Donval, J. P., Charlou, J. L., Cremière, A., & Zehnder, B. H. (2010). Experimental Study of Gas Hydrate Formation and Destabilisation Using a Novel High-Pressure Apparatus. *Marine and Petroleum Geology, 27,* 1157-1165. https://doi.org/10.1016/j.marpetgeo.2010.03.002

Seifritz, W. (1990). CO_2 Disposal by Means of Silicates. *Nature, 345,* 486. https://doi.org/10.1038/345486b0

Shukla, R., Ranjith, P., Haque, A., & Choi, X. (2010). A Review of Studies on CO_2 Sequestration and Caprock Integrity. *Fuel, 89,* 2651-2664. https://doi.org/10.1016/j.fuel.2010.05.012

Sigman, D. M., Fripiat, F., Studer, A. S., Kemeny, P. C., Martínez-García, A., Hain, M. P., Ai, X., Wang, X., Ren, H., & Haug, G. H. (2021). The Southern Ocean during the Ice Ages: A Review of the Antarctic Surface Isolation Hypothesis, with Comparison to the North Pacific. *Quaternary Science Reviews, 254,* Article 106732. https://doi.org/10.1016/j.quascirev.2020.106732

Song, J., & Zhang, D. (2013). Comprehensive Review of Caprock-Sealing Mechanisms for Geologic Carbon Sequestration. *Environmental Science & Technology, 47,* 9-22. https://doi.org/10.1021/es301610p

Sundal, A., Hellevang, H., Miri, R., Dypvik, H., Nystuen, J. P., & Aagaard, P. (2014). Variations in Mineralization Potential for CO_2 Related to Sedimentary Facies and Burial Depth—A Comparative Study from the North Sea. *Energy Procedia, 63,* 5063-5070. https://doi.org/10.1016/j.egypro.2014.11.536

Szizybalski, A., Kollersberger, T., Möller, F., Martens, S., Liebscher, A., & Kühn, M. (2014). Communication Supporting the Research on CO_2 Storage at the Ketzin Pilot Site, Germany—A Status Report after Ten Years of Public Outreach. *Energy Procedia, 51,* 274-280. https://reader.elsevier.com/reader/sd/pii/S1876610214008947?token=10B64E5A1D23D16D86B29D14466B1CE4BCAF556D3264EC284914F038F0B4716FC9FDBC1381E41B0FEBCC90BC579D72B8&originRegion=eu-west-1&originCreation=20220825114237

Talaghat, M. R., Esmaeilzadeh, F., & Fathikaljahi, J. (2009). Experimental and Theoretical Investigation of Simple Gas Hydrate Formation with or without Presence of Kinetic Inhibitors in a Flow Mini-Loop Apparatus. *Fluid Phase Equilibria, 279,* 28-40. https://doi.org/10.1016/j.fluid.2009.01.017

Tanhua, T., Orr, J. C., Lorenzoni, L., & Hansson, L. (2015). Monitoring Ocean Carbon and Ocean Acidification. *WMO Bulletin, 64.*

Tapia, J. F. D., Lee, J. Y., Ooi, R. E. H., Foo, D. C. Y., & Tan, R. R. (2018). A Review of

Optimization and Decision-Making Models for the Planning of CO_2 Capture, Utilization and Storage (CCUS) Systems. *Sustainable Production and Consumption, 13,* 1-15. https://doi.org/10.1016/j.spc.2017.10.001

Tenasaka, I. (2011). *Bridging the Commercial Gap for Carbon Capture and Storage July 2011*. Global CCS Institute.

Thomas, S. (2008). Enhanced Oil Recovery—An Overview. *Oil & Gas Science and Technology, 63,* 9-19. https://doi.org/10.2516/ogst:2007060

Trémosa, J., Castillo, C., Vong, C. Q., Kervévan, C., Lassin, A., & Audigane, P. (2014). Long-Term Assessment of Geochemical Reactivity of CO_2 Storage in Highly Saline Aquifers: Application to Ketzin, in Salah and Snøhvit Storage Sites. *International Journal of Greenhouse Gas Control, 20,* 2-26. https://doi.org/10.1016/j.ijggc.2013.10.022

Van Pham, T. H., Aagaard, P., & Hellevang, H. (2012). On the Potential for CO_2 Mineral Storage in Continental Flood Basalts—PHREEQC Batch—And 1D Diffusion-Reaction Simulations. *Geochemical Transactions, 13,* Article No. 5. https://doi.org/10.1186/1467-4866-13-5

Verdon, J. P. (2016). Using Microseismic Data Recorded at the Weyburn CCS-EOR Site to Assess the Likelihood of Induced Seismic Activity. *International Journal of Greenhouse Gas Control, 54,* 421-428. https://doi.org/10.1016/j.ijggc.2016.03.018

Wdowin, M., Tarkowski, R., & Manecki, M. (2013). Petrographic-Mineralogical and Textural Changes in Reservoir and Sealing Rocks (Zaosie Anticline) as a Result of a Long-Term Experiment in CO_2-Brine-Rock Interactions. *Gospodarka Surowcami Mineralnymi—Mineral Resources Management, 29,* 137-153. https://doi.org/10.2478/gospo-2013-0044

Wei, N., Li, X., Jiao, Z., Stauffer, P. H., Liu, S., Ellett, K., & Middleton, R. S. (2022). A Hierarchical Framework for CO_2 Storage Capacity in Deep Saline Aquifer Formations. *Frontiers in Earth Science, 9,* Article 777323. https://doi.org/10.3389/feart.2021.777323

White, D. (2009). Monitoring CO_2 Storage during EOR at the Weyburn-Midale Field. *The Leading Edge, 28,* 838-842. https://doi.org/10.1190/1.3167786

Xu, Y., Ishizaka, J., & Aoki, S. (1999). Simulations of the Distribution of Sequestered CO_2 in the North Pacific Using a Regional General Circulation Model. *Energy Conversion and Management, 40,* 683-691. https://doi.org/10.1016/S0196-8904(98)00138-1

Yamasaki, A. (2003). An Overview of CO_2 Mitigation Options for Global Warming—Emphasizing CO_2 Sequestration Options. *Journal of Chemical Engineering of Japan, 36,* 361-375. https://doi.org/10.1252/jcej.36.361

Yang, F., Pang, Z., Lin, L., Jia, Z., Zhang, F., Duan, Z., & Zong, Z. (2013). Hydrogeochemical and Isotopic Evidence for Trans-Formational Flow in a Sedimentary Basin: Implications for CO_2 Storage. *Applied Geochemistry, 30,* 4-15. https://doi.org/10.1016/j.apgeochem.2012.08.024

Yang, K., Pinker, R.T., Ma, Y., Koike, T., Wonsick, M.M., Cox, S.J., Zhang, Y.-C., and Stackhouse, P. (2008). Evaluation of Satellite Estimates of Downward Shortwave Radiation over the Tibetan Plateau. *Journal of Geophysical Research, 113,* D17204. https://doi.org/10.1029/2007JD009736

Zaluski, W., El-Kaseeh, G., Lee, S. Y., Piercey, M., & Duguid, A. (2016). Monitoring Technology Ranking Methodology for CO_2-EOR Sites Using the Weyburn-Midale Field as a Case Study. *International Journal of Greenhouse Gas Control, 54,* 466-478. https://doi.org/10.1016/j.ijggc.2016.06.012

Zangeneh, H., Jamshidi, S., & Soltanieh, M. (2013). Coupled Optimization of Enhanced Gas Recovery and Carbon Dioxide Sequestration in Natural Gas Reservoirs: Case Study in a Real Gas Field in the South of Iran. *International Journal of Greenhouse Gas Control, 17,* 515-522. https://doi.org/10.1016/j.ijggc.2013.06.007

ZeroCO$_2$ (2015). *CCS-International Legislation*. Zero Emission Resource Organisation.

Zhao, X., Liao, X., Wang, W., Chen, C., Rui, Z., & Wang, H. (2014). The CO$_2$ Storage Capacity Evaluation: Methodology and Determination of Key Factors. *Journal of the Energy Institute, 87,* 297-305. https://doi.org/10.1016/j.joei.2014.03.032

Abbreviations

ACTL	Alberta Carbon Trunk Line
CBM	Coal Bed Methane
CCS	Carbon Capture and Storage
CO$_2$CRC	The Cooperative Research Centre for Greenhouse Gas Technologies
DOE	Department of Energy
ECBM	Enhanced Coal Bed Methane recovery
EGS	Enhanced Geothermal System
EOR	Enhanced Oil Recovery
GHG	Greenhouse Gas
HCPV	Hydrocarbon Pore Volume
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied Natural Gas
MIT	Massachusetts Institute of Technology
MVA	Monitoring, Verification and Accounting
OGIP	Original Gas in Place
OOIP	Original Oil in Place
TRL	Technology Readiness Level
UKCCSRC	UK Carbon Capture and Storage Research Centre
US-DOE	United States Department of Energy
USGS	United States Geological Survey
VSP	Vertical Seismic Profile
XRD	X-Ray Diffraction

Appendix 1

Table A1. Worldwide CCS initiatives encompassing large-scale commercial projects that have been previously operational and pilot development operations (MIT, 2015; Shukla et al., 2010; Global CCS Institute—CO_2RE).

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
In Salah CO_2 Storage	Commercial CCS Facility	Completed	Algeria	2004	Natural Gas Processing
Bridgeport Energy Moonie CCUS project	Commercial CCS Facility	Advanced Development	Australia	2023	CO_2 Transport and Storage
Burrup CCS Hub	Commercial CCS Facility	Early Development	Australia		CO_2 Transport and Storage
Callide Oxyfuel Project	Pilot and Demonstration CCS Facility	Completed	Australia	2012	Power Generation
CarbonNet	Commercial CCS Facility	Advanced Development	Australia		CO_2 Transport and Storage
Cliff Head CCS Project (Mid West Clean Energy Project)	Commercial CCS Facility	Advanced Development	Australia	2025	CO_2 Transport and Storage
CO_2CRC Otway	Pilot and Demonstration CCS Facility	Operational	Australia	2008	Natural Gas Processing
CTSCo Surat Basin CCS Project	Pilot and Demonstration CCS Facility	Advanced Development	Australia	2023	Power Generation
Gorgon Carbon Dioxide Injection	Commercial CCS Facility	Operational	Australia	2019	Natural Gas Processing
Hazelwood Carbon Capture and Mineral Sequestration Pilot Plant	Pilot and Demonstration CCS Facility	Completed	Australia	2009	Power Generation
Hydrogen Energy Supply Chain (HESC) project	Commercial CCS Facility	Advanced Development	Australia		Hydrogen Production
Hydrogen Energy Supply Chain (HESC) project	Pilot and Demonstration CCS Facility	Completed	Australia	2028	Hydrogen Production
INPEX CCS Project Darwin	Commercial CCS Facility	Early Development	Australia	2026	Natural Gas Processing
Mid-West Modern Energy Hub	Commercial CCS Facility	Early Development	Australia		Hydrogen Production
Moomba CCS hub (Santos Cooper Basin CCS Project)	Commercial CCS Facility	In Construction	Australia	2024	Hydrogen Production
National Geosequestration Laboratory (NGL) Australia	Pilot and Demonstration CCS Facility	Operational	Australia	2015	Research and Development
Otway Natural Gas Plant CCS	Commercial CCS Facility	Early Development	Australia	2026	Natural Gas Processing
Post-Combustion Capture (PCC)@CSIRO	Pilot and Demonstration CCS Facility	Operational	Australia	2005	Power Generation
South East Australia Carbon Capture Hub	Commercial CCS Facility	Early Development	Australia	2025	Natural Gas Processing
South West Hub	Pilot and Demonstration CCS Facility	Completed	Australia		Fertiliser Production

Continued

Wallumbilla Renewable Methane Demonstration Project	Pilot and Demonstration CCS Facility	Advanced Development	Australia	2021	Direct Air Capture
Antwerp@C—BASF Antwerp CCS	Commercial CCS Facility	Advanced Development	Belgium	2030	Chemical Production
Antwerp@C—Exxonmobil Antwerp Refinery CCS	Commercial CCS Facility	Early Development	Belgium	2030	Chemical Production
Antwerp@C—Borealis Antwerp CCS	Commercial CCS Facility	Early Development	Belgium	2030	Chemical Production
Antwerp@C—Ineos Antwerp CCS	Commercial CCS Facility	Early Development	Belgium	2030	Chemical Production
LEILAC	Pilot and Demonstration CCS Facility	In Construction	Belgium	2025	Cement Production
Steelanol	Utilisation Facilities	Operational	Belgium	2023	Iron and Steel Production
FS Lucas do Rio Verde BECCS Project	Commercial CCS Facility	Early Development	Brazil		Ethanol Production
Miranga CO_2 Injection Project	Pilot and Demonstration CCS Facility	Completed	Brazil	2009	Fertiliser Production
Petrobras Santos Basin Pre-Salt Oil Field CCS	Commercial CCS Facility	Operational	Brazil	2008	Natural Gas Processing
Air Products Net-Zero Hydrogen Energy Complex	Commercial CCS Facility	Advanced Development	Canada	2024	Hydrogen Production
Alberta Carbon Conversion Technology Centre (ACCTC)	Pilot and Demonstration CCS Facility	Operational	Canada	2018	Power Generation
Alberta Carbon Trunk Line (ACTL)	Commercial CCS Facility	Operational	Canada	2020	CO_2 Transport and Storage
Blue But Better	Commercial CCS Facility	In Construction	Canada	2024	Hydrogen Production
Boundary Dam Unit 3 Carbon Capture and Storage Facility (BD3 CCS facility)	Commercial CCS Facility	Operational	Canada	2014	Power Generation
Capital Power Genesee CCS Project	Commercial CCS Facility	Advanced Development	Canada	2026	Power Generation
Caroline Carbon Capture Power Complex	Commercial CCS Facility	Early Development	Canada	2025	Power Generation
CMC Research Institutes (CMCRI)	Pilot and Demonstration CCS Facility	Operational	Canada	2018	Research and Development
CO_2 Solutions Valleyfield Carbon Capture Demonstration Project	Pilot and Demonstration CCS Facility	Completed	Canada	2015	Research and Development
Enhance Energy Clive CO_2-EOR (ACTL)	Commercial CCS Facility	Operational	Canada	2020	CO_2 Transport and Storage
Federated Co-operatives Limited (Ethanol)	Commercial CCS Facility	Advanced Development	Canada	2024	Ethanol Production

Continued

Federated Co-operatives Limited (Refinery)	Commercial CCS Facility	Advanced Development	Canada	2026	Oil Refining
Glacier Gas Plant MCCS	Commercial CCS Facility	Operational	Canada	2022	Natural Gas Processing
Husky Energy Lashburn and Tangleflags CO_2 Injection in Heavy Oil Reservoirs Project	Pilot and Demonstration CCS Facility	Operational	Canada	2012	Ethanol Production
Nauticol Energy Net Zero Methanol (ACTL)	Commercial CCS Facility	Early Development	Canada	2025	Methanol Production
Northwest Redwater CO_2 Recovery Unit Sturgeon Refinery (ACTL)	Commercial CCS Facility	Operational	Canada	2020	Oil Refining
Origins Project Carbon Storage Hub	Commercial CCS Facility	Early Development	Canada	2026	CO_2 Transport and Storage
Pembina Cardium CO_2 Monitoring Pilot	Pilot and Demonstration CCS Facility	Completed	Canada	2005	Natural Gas Processing
Polaris CCS Project	Commercial CCS Facility	Early Development	Canada	2025	Hydrogen Production
Quest	Commercial CCS Facility	Operational	Canada	2015	Hydrogen Production
Saskatchewan NET Power Plant	Commercial CCS Facility	Early Development	Canada	2025	Power Generation
Shand Carbon Capture Test Facility (CCTF)	Pilot and Demonstration CCS Facility	Operational	Canada	2015	Research and Development
Southeast Saskatchewan CCUS Hub-Storage	Commercial CCS Facility	Advanced Development	Canada		CO_2 Transport and Storage
Svante and Husky Energy VeloxoTherm Capture Process Test	Pilot and Demonstration CCS Facility	Advanced Development	Canada	2018	Oil Refining
WCS Redwater CO_2 Recovery Unit (ACTL)	Commercial CCS Facility	Operational	Canada	2020	Fertiliser Production
Zama Field Validation Test	Pilot and Demonstration CCS Facility	Completed	Canada	2005	Natural Gas Processing
Australia-China Post Combustion Capture (PCC) Feasibility Study Project	Pilot and Demonstration CCS Facility	Completed	China	2010	Power Generation
Australia-China Post Combustion Capture (PCC) Feasibility Study Project	Pilot and Demonstration CCS Facility	Completed	China	2010	Power Generation
China Coalbed Methane Technology Sequestration Project	Pilot and Demonstration CCS Facility	Completed	China	2004	Research and Development
China National Energy Guohua Jinjie	Commercial CCS Facility	Operational	China	2020	Power Generation
China National Energy Taizhou	Commercial CCS Facility	In Construction	China	2023	Power Generation

Continued

Chinese-European Emission-Reducing Solutions (CHEERS)	Pilot and Demonstration CCS Facility	Advanced Development	China	2022	Oil Refining
CNOOC Enping CCS Offshore Project	Commercial CCS Facility	Operational	China	2023	Natural Gas Processing
CNPC Jilin Oil Field CO_2 EOR	Commercial CCS Facility	Operational	China	2018	Natural Gas Processing
CNPC Jilin Oil Field EOR Demonstration Project	Pilot and Demonstration CCS Facility	Completed	China	2008	Natural Gas Processing
Daqing Oil Field EOR Demonstration Project	Pilot and Demonstration CCS Facility	Operational	China	2003	Natural Gas Processing
Guanghui Energy CCUS	Commercial CCS Facility	In Construction	China		Methanol Production
Haifeng Carbon Capture Test Platform	Pilot and Demonstration CCS Facility	Operational	China	2018	Power Generation
Huaneng GreenGen IGCC Demonstration-scale System (Phase 2)	Pilot and Demonstration CCS Facility	In Construction	China	2025	Power Generation
Huaneng Longdong Energy Base Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	China	2023	Power Generation
ITRI Calcium Looping Pilot	Pilot and Demonstration CCS Facility	Operational	China	2013	Cement Production
Jinling Petrochemical CCUS (Nanjing Refinery)	Commercial CCS Facility	Operational	China	2023	Oil Refining
Karamay Dunhua Oil Technology CCUS EOR Project	Commercial CCS Facility	Operational	China	2015	Methanol Production
PetroChina Changqing Oil Field EOR CCUS	Pilot and Demonstration CCS Facility	Operational	China	2017	Fuel transformation
Shenhua Group Ordos Carbon Capture and Storage (CCS) Demonstration Project	Pilot and Demonstration CCS Facility	Completed	China	2011	Fuel transformation
Shuncheng CO_2-TO-METHANOL Anyang Petrochemical	Utilisation Facilities	Operational	China	2022	Chemical Production
Sinopec Nanjing Chemical Industries CCUS Cooperation Project	Commercial CCS Facility	Operational	China	2021	Chemical Production
Sinopec Qilu-Shengli CCUS Project	Commercial CCS Facility	Operational	China	2022	Chemical Production
Sinopec Shengli Oilfield Carbon Capture Utilization and Storage Pilot Project	Pilot and Demonstration CCS Facility	Operational	China	2010	Power Generation
Sinopec Shengli Power Plant CCS	Commercial CCS Facility	Advanced Development	China	2025	Power Generation
Sinopec Zhongyuan Carbon Capture Utilization and Storage	Pilot and Demonstration CCS Facility	Completed	China	2006	Chemical Production

Continued

Yanchang Integrated CCS Demonstration	Commercial CCS Facility	Operational	China	2012	Chemical Production
Geothermal Plant with CO_2 Re-injection	Pilot and Demonstration CCS Facility	Operational	Croatia	2018	Power Generation
CASTOR	Pilot and Demonstration CCS Facility	Completed	Denmark	2006	Power Generation
CESAR	Pilot and Demonstration CCS Facility	Completed	Denmark	2008	Power Generation
Copenhill (Amager Bakke) Waste to Energy CCS	Commercial CCS Facility	Advanced Development	Denmark	2025	Waste Incineration
Greenport Scandinavia	Commercial CCS Facility	Early Development	Denmark	2025	Bioenergy
Project Greensand	Commercial CCS Facility	Advanced Development	Denmark	2025	CO_2 Transport and Storage
Air Liquide CalCC	Commercial CCS Facility	Early Development	France	2028	Lime Production
Air Liquide Normandy CCS	Commercial CCS Facility	Early Development	France	2025	Hydrogen Production
C2A2 Field Pilot—Le Havre	Pilot and Demonstration CCS Facility	Completed	France	2013	Power Generation
DMX^{TM} Demonstration in Dunkirk	Pilot and Demonstration CCS Facility	Operational	France	2022	Iron and Steel Production
K6	Commercial CCS Facility	Early Development	France	2028	Cement Production
Lacq CCS Pilot Project	Pilot and Demonstration CCS Facility	Completed	France	2010	Power Generation
CEMEX, Rüdersdorf, Germany	Commercial CCS Facility	Early Development	Germany	2026	Cement Production
Ketzin Pilot Project	Pilot and Demonstration CCS Facility	Completed	Germany	2004	Power Generation
Schwarze Pumpe Oxy-fuel Pilot Plant	Pilot and Demonstration CCS Facility	Completed	Germany	2008	Power Generation
Wilhelmshaven CO_2 Capture Pilot Plant	Pilot and Demonstration CCS Facility	Completed	Germany	2012	Power Generation
MOL Szank field CO_2 EOR	Commercial CCS Facility	Operational	Hungary	1992	Natural Gas Processing
CarbFix Project	Pilot and Demonstration CCS Facility	Operational	Iceland	2012	Power Generation
CODA Shipping	Commercial CCS Facility	Advanced Development	Iceland	2026	CO_2 Transport and Storage
CODA Terminal Onshore Infrastructure	Commercial CCS Facility	Advanced Development	Iceland	2026	CO_2 Transport and Storage
CODA Terminal Pipeline	Commercial CCS Facility	Advanced Development	Iceland	2026	CO_2 Transport and Storage

Continued

CODA Terminal Storage	Commercial CCS Facility	Advanced Development	Iceland	2026	CO_2 Transport and Storage
Mammoth	Commercial CCS Facility	In Construction	Iceland	2024	Direct Air Capture
Orca	Commercial CCS Facility	Operational	Iceland	2021	Direct Air Capture
Carbon Clean Solutions Solvay Vishnu Capture Project	Pilot and Demonstration CCS Facility	Completed	India	2012	Power Generation
NTPC Vindhyachal Super Thermal Power Station CCS	Utilisation Facilities	Operational	India	2022	Power Generation
Tata Steel Jamshedpur Steel Plant	Pilot and Demonstration CCS Facility	Operational	India	2021	Iron and Steel Production
Tuticorin (TTPS)—Carbon Clean Solution	Utilisation Facilities	Operational	India	2016	Power Generation
Tuticorin Alkali Chemicals and Fertilizers Ltd	Pilot and Demonstration CCS Facility	Operational	India	2016	Chemical Production
Arun CCS Hub	Commercial CCS Facility	Early Development	Indonesia	2029	CO_2 Transport and Storage
Gundih CCS Pilot	Pilot and Demonstration CCS Facility	Advanced Development	Indonesia	2025	Natural Gas Processing
PAU Central Sulawesi Clean Fuel Ammonia Production with CCUS	Commercial CCS Facility	Early Development	Indonesia	2025	Fertiliser Production
Repsol Sakakemang Carbon Capture and Injection	Commercial CCS Facility	Early Development	Indonesia	2026	Natural Gas Processing
Sukowati CCUS	Commercial CCS Facility	Early Development	Indonesia	2028	Oil Refining
Ervia Cork CCS	Commercial CCS Facility	Early Development	Ireland	2028	Power Generation
Heletz, Israel pilot CO_2 injection site	Pilot and Demonstration CCS Facility	Completed	Israel	2026	Research and Development
Brindisi CO_2 Capture Pilot Plant	Pilot and Demonstration CCS Facility	Completed	Italy	2010	Power Generation
Ravenna CCS Hub	Commercial CCS Facility	Early Development	Italy	2027	CO_2 Transport and Storage
COURSE 50—CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50	Pilot and Demonstration CCS Facility	Operational	Japan	2008	Iron and Steel Production
EAGLE	Pilot and Demonstration CCS Facility	Completed	Japan	2002	Power Generation
Kashiwazaki Clean Hydrogen/Ammonia Project	Pilot and Demonstration CCS Facility	In Construction	Japan	2024	Hydrogen Production
Mikawa Post Combustion Capture Demonstration Plant	Pilot and Demonstration CCS Facility	Operational	Japan	2020	Power Generation

Continued

Nagaoka CO_2 Storage Project	Pilot and Demonstration CCS Facility	Completed	Japan	2003	Natural Gas Processing
Osaki CoolGen Project	Pilot and Demonstration CCS Facility	In Construction	Japan	2020	Power Generation
Taiheiyo Cement Corporation	Pilot and Demonstration CCS Facility	Operational	Japan	2021	Cement Production
Tomakomai CCS Demonstration Project	Pilot and Demonstration CCS Facility	Operational	Japan	2016	Hydrogen Production
Kasawari	Commercial CCS Facility	In Construction	Malaysia	2025	Natural Gas Processing
Lang Lebah CCS	Commercial CCS Facility	Advanced Development	Malaysia	2026	Natural Gas Processing
Air Liquide Refinery Rotterdam CCS	Commercial CCS Facility	Advanced Development	Netherlands	2024	Hydrogen Production
Air Products Refinery Rotterdam CCS	Commercial CCS Facility	Advanced Development	Netherlands	2024	Hydrogen Production
Buggenum Carbon Capture (CO_2 Catch-up) Pilot Project	Pilot and Demonstration CCS Facility	Completed	Netherlands	2011	Power Generation
Delta Corridor Pipeline Network	Commercial CCS Facility	Early Development	Netherlands	2026	CO_2 Transport and Storage
ExxonMobil Benelux Refinery CCS	Commercial CCS Facility	Advanced Development	Netherlands	2024	Hydrogen Production
Hydrogen 2 Magnum (H2M)	Commercial CCS Facility	Early Development	Netherlands	2024	Power Generation
K12-B CO_2 Injection Project	Pilot and Demonstration CCS Facility	Completed	Netherlands	2004	Natural Gas Processing
L10 Carbon Capture and Storage	Commercial CCS Facility	Early Development	Netherlands	2026	Hydrogen Production
Porthos—Compressor Station	Commercial CCS Facility	Advanced Development	Netherlands	2024	CO_2 Transport and Storage
Porthos—Offshore Pipeline	Commercial CCS Facility	Advanced Development	Netherlands	2024	CO_2 Transport and Storage
Porthos—Onshore Pipeline	Commercial CCS Facility	Advanced Development	Netherlands	2024	CO_2 Transport and Storage
Porthos Storage	Commercial CCS Facility	Advanced Development	Netherlands	2024	CO_2 Transport and Storage
Shell Energy and Chemicals Park Rotterdam	Commercial CCS Facility	In Construction	Netherlands	2024	Bioenergy
Yara Sluiskil	Commercial CCS Facility	Early Development	Netherlands	2025	Fertiliser Production
Zeeland Refinery Azur	Commercial CCS Facility	Early Development	Netherlands	2026	Hydrogen Production
Project Pouakai Hydrogen Production with CCS	Commercial CCS Facility	Early Development	New Zealand	2024	Hydrogen Production

Continued

Barents Blue	Commercial CCS Facility	Early Development	Norway	2025	Fertiliser Production
Borg CO_2	Commercial CCS Facility	Early Development	Norway		CO_2 Transport and Storage
CEMCAP	Pilot and Demonstration CCS Facility	Completed	Norway	2015	Cement Production
CO_2 Capture Test Facility at Norcem Brevik	Pilot and Demonstration CCS Facility	Completed	Norway	2013	Cement Production
Equinor Smeaheia (Norway)	Commercial CCS Facility	Early Development	Norway	2028	CO_2 Storage
Fortum Oslo Varme—Shipping Route	Commercial CCS Facility	Early Development	Norway	2025	Waste Incineration
Hafslund Oslo Celsio	Commercial CCS Facility	In Construction	Norway	2024	Waste Incineration
Hafslund Oslo Celsio—Truck Route	Commercial CCS Facility	Advanced Development	Norway	2025	Waste Incineration
Norcem Brevik—Cement Plant	Commercial CCS Facility	In Construction	Norway	2024	Cement Production
Norcem Brevik—Shipping Route	Commercial CCS Facility	In Construction	Norway	2024	Cement Production
Northern Lights—Pipeline	Commercial CCS Facility	Early Development	Norway	2024	CO_2 Transport and Storage
Northern Lights—Storage	Commercial CCS Facility	In Construction	Norway	2024	CO_2 Transport and Storage
Polaris Carbon Storage	Commercial CCS Facility	Advanced Development	Norway	2024	Hydrogen Production
Sleipner CCS Project	Commercial CCS Facility	Operational	Norway	1996	Natural Gas Processing
Snohvit CO_2 Storage	Commercial CCS Facility	Operational	Norway	2008	Natural Gas Processing
Technology Centre Mongstad (TCM)	Pilot and Demonstration CCS Facility	Operational	Norway	2012	Oil Refining
Project Hajar	Commercial CCS Facility	In Construction	Oman	2024	Direct Air Capture
Papua LNG CCS	Commercial CCS Facility	Early Development	Papua New Guinea	2027	Natural Gas Processing
GO4ECOPLANET	Commercial CCS Facility	Early Development	Poland	2027	Cement Production
North Field East Project (NFE) CCS	Commercial CCS Facility	In Construction	Qatar	2025	Natural Gas Processing
Qatar LNG CCS	Commercial CCS Facility	Operational	Qatar	2019	Natural Gas Processing
Novatek Yamal LNG CCS	Commercial CCS Facility	Early Development	Russia	2027	Natural Gas Processing
Uthmaniyah CO_2-EOR Demonstration	Commercial CCS Facility	Operational	Saudi Arabia	2015	Natural Gas Processing
Pilot Carbon Storage Project (PCSP)—Zululand Basin, South Africa	Pilot and Demonstration CCS Facility	Advanced Development	South Africa	2020	Under Evaluation

Continued

Boryeong—KoSol Process for CO_2 Capture (KPCC) Test	Pilot and Demonstration CCS Facility	Completed	South Korea	2010	Power Generation
Hadong—Dry-sorbent CO_2 Capture System Test	Pilot and Demonstration CCS Facility	Completed	South Korea	2014	Power Generation
Korea-CCS 1 & 2	Commercial CCS Facility	Early Development	South Korea	2025	Power Generation
CIUDEN: CO_2 Capture & Transport Technology Development Plant	Pilot and Demonstration CCS Facility	Completed	Spain	2012	Power Generation
CIUDEN: CO_2 Storage Technology Development Plant	Pilot and Demonstration CCS Facility	Operational	Spain	2015	Research and Development
ELCOGAS Pre-combustion Carbon Capture Pilot Project: Puertollano	Pilot and Demonstration CCS Facility	Completed	Spain	2010	Power Generation
La Pereda Calcium Looping Pilot Plant	Pilot and Demonstration CCS Facility	Completed	Spain	2012	Power Generation
Cementa CCS (Slite Cement plant)	Commercial CCS Facility	Early Development	Sweden	2030	Cement Production
Cinfracap—Pipeline	Commercial CCS Facility	Early Development	Sweden	2026	CO_2 Transport and Storage
Cinfracap—Shipping Route	Commercial CCS Facility	Early Development	Sweden	2026	CO_2 Transport and Storage
Karlshamn Field Pilot	Pilot and Demonstration CCS Facility	Completed	Sweden	2009	Power Generation
Preem Refinery CCS	Commercial CCS Facility	Early Development	Sweden	2025	Hydrogen Production
STEPWISE Pilot of SEWGS Technology at Swerea/Mefos	Pilot and Demonstration CCS Facility	Operational	Sweden	2017	Iron and Steel Production
Stockholm Exergi BECCS	Commercial CCS Facility	Advanced Development	Sweden	2027	Bioenergy
Stockholm Exergi BECCS—Shipping Route	Commercial CCS Facility	Advanced Development	Sweden	2027	Bioenergy
PTTEP Arthit CCS	Commercial CCS Facility	Advanced Development	Thailand	TBC	Natural Gas Processing
Bayu-Undan CCS	Commercial CCS Facility	Advanced Development	Timor-Leste	2027	Natural Gas Processing
Abu Dhabi CCS (Phase 1 being Emirates Steel Industries)	Commercial CCS Facility	Operational	United Arab Emirates	2016	Iron and Steel Production
Abu Dhabi CCS Phase 2: Natural gas processing plant	Commercial CCS Facility	Advanced Development	United Arab Emirates	2025	Natural Gas Processing
Ghasha Concession Fields	Commercial CCS Facility	Advanced Development	United Arab Emirates	2025	Natural Gas Processing

Continued

Aberthaw Pilot Carbon Capture Facility	Pilot and Demonstration CCS Facility	Completed	United Kingdom	2013	Power Generation
Acorn	Commercial CCS Facility	Early Development	United Kingdom	2024	Hydrogen Production
Acorn (Minimum Viable CCS Development)	Pilot and Demonstration CCS Facility	Advanced Development	United Kingdom	2025	CO_2 Transport and Storage
Acorn CO_2 Pipeline	Commercial CCS Facility	Early Development	United Kingdom	2026	CO_2 Transport and Storage
Acorn Direct Air Capture Facility	Commercial CCS Facility	Early Development	United Kingdom	2026	Hydrogen Production
Acorn Hydrogen	Commercial CCS Facility	Early Development	United Kingdom	2025	Hydrogen Production
Acorn Storage Site	Commercial CCS Facility	Advanced Development	United Kingdom	2025	CO_2 Transport and Storage
Buxton Lime Net Zero	Commercial CCS Facility	Early Development	United Kingdom	2024	Lime Production
Caledonia Clean Energy	Commercial CCS Facility	Early Development	United Kingdom	2025	Power Generation
CF Fertilisers Billingham Ammonia CCS	Commercial CCS Facility	Early Development	United Kingdom	2023	Fertiliser Production
Damhead Pipeline (Medway Hub)	Commercial CCS Facility	Early Development	United Kingdom		Power Generation
Damhead Power Station (Medway)	Commercial CCS Facility	Early Development	United Kingdom		Power Generation
Drax BECCS Project	Commercial CCS Facility	Early Development	United Kingdom	2027	Power Generation
Drax bioenergy carbon capture pilot plant	Pilot and Demonstration CCS Facility	Operational	United Kingdom	2019	Power Generation
East Coast Cluster Humber Pipeline	Commercial CCS Facility	Advanced Development	United Kingdom	2025	CO_2 Transport and Storage
East Coast Cluster Teesside Pipeline	Commercial CCS Facility	Advanced Development	United Kingdom	2025	CO_2 Transport and Storage
Endurance Storage Site	Commercial CCS Facility	Advanced Development	United Kingdom	2025	CO_2 Transport and Storage
Esmond and Forbes Carbon Storage (Medway Hub)	Commercial CCS Facility	Early Development	United Kingdom		Power Generation
Ferrybridge Carbon Capture Pilot (CCPilot100+)	Pilot and Demonstration CCS Facility	Completed	United Kingdom	2011	Power Generation
Grain Power Station (Medway)	Commercial CCS Facility	Early Development	United Kingdom		Power Generation
H2NorthEast	Commercial CCS Facility	Early Development	United Kingdom	2027	Hydrogen Production

Continued

Hydrogen to Humber Saltend	Commercial CCS Facility	Early Development	United Kingdom	2025	Hydrogen Production
HyNet Hydrogen Production Project (HPP)	Commercial CCS Facility	Early Development	United Kingdom	2025	Hydrogen Production
HyNet North West	Commercial CCS Facility	Early Development	United Kingdom	2026	Hydrogen Production
HyNet North West—Hanson Cement CCS	Commercial CCS Facility	Early Development	United Kingdom	2026	Cement Production
HyNet Pipeline	Commercial CCS Facility	Early Development	United Kingdom	2025	CO_2 Transport and Storage
Hynet Storage Site	Commercial CCS Facility	Early Development	United Kingdom	2025	CO_2 Transport and Storage
Isle of Grain LNG Terminal (Medway Hub)	Commercial CCS Facility	Early Development	United Kingdom	2026	Power Generation
Keady 3 CCS Power Station	Commercial CCS Facility	Early Development	United Kingdom	2027	Power Generation
Killingholme Power Station	Commercial CCS Facility	Early Development	United Kingdom	2027	Hydrogen Production
Medway Hub Shipping	Commercial CCS Facility	Early Development	United Kingdom		Power Generation
Medway Power Station	Commercial CCS Facility	Early Development	United Kingdom		Power Generation
NET Power Plant (East Coast Cluster)	Commercial CCS Facility	Early Development	United Kingdom	2025	Power Generation
Net Zero Teesside—CCGT Facility	Commercial CCS Facility	Early Development	United Kingdom	2025	Power Generation
Net Zero Teesside—BP H2Teesside	Commercial CCS Facility	Early Development	United Kingdom	2027	Hydrogen Production
Northern Gas Network H21 North of England	Commercial CCS Facility	Early Development	United Kingdom	2026	Hydrogen Production
Pembroke Power Station	Commercial CCS Facility	Early Development	United Kingdom	2030	Power Generation
Peterhead CCS Power Station	Commercial CCS Facility	Advanced Development	United Kingdom	2026	Power Generation
Phillips 66 Humber Refinery CCS	Commercial CCS Facility	Advanced Development	United Kingdom	2028	Hydrogen Production
Prax Lindsey Carbon Capture Project (PLCCP)	Commercial CCS Facility	Advanced Development	United Kingdom	2028	Oil Refining
Redcar Energy Centre	Commercial CCS Facility	Early Development	United Kingdom	2025	Power Generation
Renfrew Oxy-fuel (Oxycoal 2) Project	Pilot and Demonstration CCS Facility	Completed	United Kingdom	2007	Power Generation

Continued

Suez Waste to Energy CCS (East Coast Cluster)	Commercial CCS Facility	Early Development	United Kingdom	2027	Waste Incineration
Tees Valley Energy Recovery Facility Project (TVERF)	Commercial CCS Facility	Early Development	United Kingdom	2026	Bioenergy
UKCCSRC Pilot-scale Advanced Capture Technology (PACT)	Pilot and Demonstration CCS Facility	Completed	United Kingdom	2012	Power Generation
Vertex Hydrogen	Commercial CCS Facility	Early Development	United Kingdom	2025	Oil Refining
Viking CCS Pipeline	Commercial CCS Facility	Advanced Development	United Kingdom	2027	CO_2 Transport and Storage
Viking CCS Storage Site	Commercial CCS Facility	Advanced Development	United Kingdom	2027	CO_2 Transport and Storage
Viridor Runcorn Carbon Capture	Commercial CCS Facility	Early Development	United Kingdom		Waste Incineration
VPI Immingham Power Plant CCS	Commercial CCS Facility	Advanced Development	United Kingdom	2027	Power Generation
Whitetail Clean Energy	Commercial CCS Facility	Early Development	United Kingdom		Power Generation
ADM Illinois Industrial	Commercial CCS Facility	Operational	USA	2017	Ethanol Production
ArcelorMittal Texas (formerly voestalpine Texas)	Commercial CCS Facility	Early Development	USA		Iron and Steel Production
Arkalon CO_2 Compression Facility	Commercial CCS Facility	Operational	USA	2009	Ethanol Production
Ascension Clean Energy (Louisiana)	Commercial CCS Facility	Early Development	USA	2027	Hydrogen Production
Atkinson Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Bayou Bend CCS	Commercial CCS Facility	Advanced Development	USA	2025	CO_2 Transport and Storage
Baytown Low Carbon Hydrogen	Commercial CCS Facility	Advanced Development	USA	2027	Hydrogen Production
Bell Creek—Incidental CO_2 Storage Associated with a Commercial EOR Project	Pilot and Demonstration CCS Facility	Operational	USA	2010	Natural Gas Processing
Bonanza BioEnergy CCUS EOR	Commercial CCS Facility	Operational	USA	2012	Ethanol Production
Borger CO_2 Compression Facility	Commercial CCS Facility	Completed	USA	2001	Fertiliser Production
Bushmills Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Cal Capture	Commercial CCS Facility	Advanced Development	USA	2027-28	Power Generation
Cane Run CCS	Commercial CCS Facility	Early Development	USA		Power Generation

Continued

Carbon TerraVault I Project	Commercial CCS Facility	Early Development	USA	2025	CO_2 Transport and Storage
CarbonFree Skymine	Utilisation Facilities	Operational	USA	2015	Cement Production
Casselton Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Central City Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Central Louisiana Regional Carbon Storage (CENLA) Hub	Commercial CCS Facility	In Construction	USA	2027	CO_2 Transport and Storage
Century Plant	Commercial CCS Facility	Operational	USA	2010	Natural Gas Processing
Clean Energy Systems BiCRS Plant—Madera County	Commercial CCS Facility	Early Development	USA	2027	Power Generation
Clean Energy Systems Carbon Negative Energy Plant—Central Valley	Commercial CCS Facility	Early Development	USA	2025	Power Generation
CO_2 Sequestration Field Test: Deep Unminable Lignite Seam	Pilot and Demonstration CCS Facility	Completed	USA	2009	Research and Development
Coastal Bend CCS	Commercial CCS Facility	Early Development	USA	2026	CO_2 Transport and Storage
Coffeyville Gasification Plant	Commercial CCS Facility	Operational	USA	2013	Fertiliser Production
Core Energy CO_2-EOR	Commercial CCS Facility	Operational	USA	2003	Natural Gas Processing
Coyote Clean Power Project	Commercial CCS Facility	Advanced Development	USA	2025	Power Generation
CPV Shay Energy Center (CPV West Virginia Natural Gas Power Station CCS)	Commercial CCS Facility	Early Development	USA		Power Generation
Cranfield Project	Pilot and Demonstration CCS Facility	Operational	USA	2009	Research and Development
Cyclus Power Generation	Commercial CCS Facility	Early Development	USA		Bioenergy
Dave Johnston Plant Carbon Capture	Commercial CCS Facility	Early Development	USA	2025	Power Generation
Deer Park Energy Centre CCS Project	Commercial CCS Facility	Advanced Development	USA		Power Generation
Diamond Vault CCS	Commercial CCS Facility	Early Development	USA	2028	Power Generation
Donaldsonville	Commercial CCS Facility	In Construction	USA	2025	Ammonia Production
Dry Fork Integrated Commercial Carbon Capture and Storage (CCS)	Commercial CCS Facility	Early Development	USA	2025	Power Generation
E.W. Brown 0.7 MWe Pilot Carbon Capture Unit	Pilot and Demonstration CCS Facility	Operational	USA	2014	Power Generation

Continued

El Dorado CCS Project	Commercial CCS Facility	Early Development	USA	2026	Fertiliser Production
Enid Fertilizer	Commercial CCS Facility	Operational	USA	1982	Fertiliser Production
Fairmont Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Farley DAC Project	Commercial CCS Facility	Advanced Development	USA		Direct Air Capture
Farnsworth Unit EOR Field Project—Development Phase	Pilot and Demonstration CCS Facility	Operational	USA	2013	Ethanol Production
Freeport LNG CCS project	Commercial CCS Facility	Cancelled	USA	2024	Natural Gas Processing
Frio Brine Pilot	Pilot and Demonstration CCS Facility	Completed	USA	2004	Research and Development
Fuel Cell Carbon Capture Pilot Plant	Pilot and Demonstration CCS Facility	Operational	USA	2016	Power Generation
G2 Net-Zero LNG	Commercial CCS Facility	Early Development	USA		Natural Gas Processing
Galva Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Gerald Gentleman Station Carbon Capture	Commercial CCS Facility	Advanced Development	USA	2025	Power Generation
Goldfield Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Grand Forks Blue Ammonia Capture plant	Commercial CCS Facility	Early Development	USA		Natural Gas Processing
Grand Junction Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Granite Falls Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Great Plains Synfuels Plant and Weyburn-Midale	Commercial CCS Facility	Operational	USA	2000	Hydrogen Production
Hackberry Carbon Sequestration Project (Sempra)	Commercial CCS Facility	Early Development	USA		CO_2 Transport and Storage
Haynesville Gas Processing (CENLA Hub)	Commercial CCS Facility	In Construction	USA	2027	Natural Gas Processing
Heartland Greenway Storage	Commercial CCS Facility	Early Development	USA	2025	Ethanol Production
Heartland Hydrogen Hub	Commercial CCS Facility	Advanced Development	USA		Power Generation
HeidelbergCement CCS	Commercial CCS Facility	Advanced Development	USA	2023	Cement Production
Heron Lake Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production

Continued

Huron Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Illinois Allam-Fetvedt cycle power plant	Commercial CCS Facility	Early Development	USA	2025	Power Generation
Illinois Basin Decatur Project (CO_2 Injection Completed, Monitoring Ongoing)	Pilot and Demonstration CCS Facility	Completed	USA	2011	Ethanol Production
James M. Barry Electric Generating Plant CCS Project	Commercial CCS Facility	Advanced Development	USA	2030	Power Generation
Kevin Dome Carbon Storage Project—Development Phase	Pilot and Demonstration CCS Facility	Completed	USA	2013	Research and Development
LafargeHolcim Cement Carbon capture	Commercial CCS Facility	Early Development	USA	2025	Cement Production
LafargeHolcim Ste. Genevieve Cement Plant CCS	Commercial CCS Facility	Early Development	USA		Cement Production
Lake Charles Methanol	Commercial CCS Facility	Advanced Development	USA	2025	Chemical Production
Lamberton Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Lawler Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Linde hydrogen plant for OCI fertilizer blue ammonia Beaumont	Commercial CCS Facility	In Construction	USA	2025	Hydrogen Production
Lone Cypress Hydrogen Project	Commercial CCS Facility	Early Development	USA	2025	Hydrogen Production
Lost Cabin Gas Plant	Commercial CCS Facility	Operational	USA	2013	Natural Gas Processing
Louisiana Clean Energy Complex	Commercial CCS Facility	In Construction	USA	2025	Hydrogen Production
Marcus Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Marshall County ECBM Project	Pilot and Demonstration CCS Facility	Completed	USA	2009	Research and Development
Mason City Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Mendota BECCS	Commercial CCS Facility	Early Development	USA	2025	Bioenergy
Merrill Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
MGSC Validation Phase (Phase II): CO_2 Storage and Enhanced Oil Recovery: Bald Unit Oil Field Test Site	Pilot and Demonstration CCS Facility	Completed	USA	2009	Research and Development
MGSC Validation Phase (Phase II): CO_2 Storage and Enhanced Oil Recovery: Sugar Creek Oil Field Test Site	Pilot and Demonstration CCS Facility	Completed	USA	2009	Research and Development

Continued

Michigan Basin (Phase II) Geologic CO_2 Sequestration Field Test	Pilot and Demonstration CCS Facility	Completed	USA	2008	Natural Gas Processing
Michigan Basin Large-Scale Injection Test	Pilot and Demonstration CCS Facility	Operational	USA	2013	Natural Gas Processing
Midwest AgEnergy Blue Flint ethanol CCS	Commercial CCS Facility	Early Development	USA	2022	Ethanol Production
Mina Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Mountaineer Validation Facility	Pilot and Demonstration CCS Facility	Completed	USA	2009	Power Generation
Mt. Simon CCS Hub (Iowa Illinois Carbon Pipeline)	Commercial CCS Facility	Early Development	USA		CO_2 Transport and Storage
Mustang Station of Golden Spread Electric Cooperative Carbon Capture	Commercial CCS Facility	Advanced Development	USA		Power Generation
National Carbon Capture Center (NCCC)	Pilot and Demonstration CCS Facility	Operational	USA	2011	Research and Development
NET Power Clean Energy Large-scale Pilot Plant	Pilot and Demonstration CCS Facility	Operational	USA	2018	Power Generation
Nevada Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
NextDecade Rio Grande LNG CCS	Commercial CCS Facility	Early Development	USA	2025	Natural Gas Processing
Norfolk Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Northern Delaware Basin CCS	Commercial CCS Facility	Advanced Development	USA	2023	Natural Gas Processing
NuDACCS—Nuclear Direct Air CCS Project	Pilot and Demonstration CCS Facility	Advanced Development	USA		Direct Air Capture
OCI Fertiliser	Commercial CCS Facility	In Construction	USA	2025	Fertiliser Production
One Earth Energy facility Carbon Capture	Commercial CCS Facility	Advanced Development	USA	2025	Ethanol Production
Onida Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Otter Tail Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Oxy-combustion of Heavy Liquid Fuels—15 MW Pilot Test	Pilot and Demonstration CCS Facility	Completed	USA	2012	Power Generation
PCS Nitrogen	Commercial CCS Facility	Operational	USA	2013	Fertiliser Production
Petra Nova Carbon Capture Project	Commercial CCS Facility	Operational	USA	2017	Power Generation

Continued

Plainview Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Plant Barry & Citronelle Integrated Project	Pilot and Demonstration CCS Facility	Completed	USA	2012	Power Generation
Plant Daniel Carbon Capture	Commercial CCS Facility	Advanced Development	USA		Power Generation
Pleasant Prairie Power Plant Field Pilot	Pilot and Demonstration CCS Facility	Completed	USA	2008	Power Generation
Polk Power Station CCS	Commercial CCS Facility	Advanced Development	USA	Under Evaluation	Power Generation
Prairie State Generating Station Carbon Capture	Commercial CCS Facility	Advanced Development	USA	2025	Power Generation
Project Interseqt—Hereford Ethanol Plant	Commercial CCS Facility	Early Development	USA	2023	Ethanol Production
Project Interseqt—Plainview Ethanol Plant	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Project Tundra	Commercial CCS Facility	Advanced Development	USA	2026	Power Generation
Red Trail Energy CCS	Commercial CCS Facility	Operational	USA	2022	Ethanol Production
Redfield Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
River Bend CCS Louisiana Pipeline	Commercial CCS Facility	Early Development	USA	2026	CO_2 Transport and Storage
San Juan Basin ECBM Storage Test	Pilot and Demonstration CCS Facility	Completed	USA	2008	Research and Development
Shenandoah Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Shute Creek Gas Processing Plant	Commercial CCS Facility	Operational	USA	1986	Natural Gas Processing
Sioux Center Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Steamboat Rock Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
STRATOS (1PointFive Direct Air Capture)	Commercial CCS Facility	In Construction	USA	2024	Direct Air Capture
Summit Carbon Solutions—Storage	Commercial CCS Facility	Advanced Development	USA	2024	CO_2 Transport and Storage
Summit Pipeline	Commercial CCS Facility	Advanced Development	USA	2024	Bioenergy
Superior Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production

Continued

Terrell Natural Gas Processing Plant (formerly Val Verde Natural Gas Plants)	Commercial CCS Facility	Operational	USA	1972	Natural Gas Processing
The Illinois Clean Fuels Project	Commercial CCS Facility	Early Development	USA	2025	Chemical Production
Valero Port Arthur Refinery	Commercial CCS Facility	Operational	USA	2013	Hydrogen Production
Velocys' Bayou Fuels Negative Emission Project	Commercial CCS Facility	Early Development	USA	2026	Chemical Production
Wabash CO_2 Sequestration	Commercial CCS Facility	Advanced Development	USA	2022	Fertiliser Production
Watertown Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Wentworth Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
West Pearl Queen CO_2 Sequestration Pilot Test and Modelling Project	Pilot and Demonstration CCS Facility	Completed	USA	2002	Research and Development
Wood River Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production
Wyoming Integrated Test Center (ITC)	Pilot and Demonstration CCS Facility	Operational	USA	2018	Power Generation
York Biorefinery Carbon Capture and Storage	Commercial CCS Facility	Advanced Development	USA	2024	Ethanol Production