

Review

A Comprehensive Review on Carbon Dioxide Sequestration Methods

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Abstract: Capturing and storing CO₂ (CCS) was once regarded as a significant, urgent, and necessary option for reducing the emissions of CO₂ from coal and oil and gas industries and mitigating the serious impacts of CO₂ on the atmosphere and the environment. This recognition came about as a result of extensive research conducted in the past. The CCS cycle comes to a close with the last phase of CO₂ storage, which is accomplished primarily by the adsorption of CO₂ in the ocean and injection of CO₂ subsurface reservoir formation, in addition to the formation of limestone via the process of CO₂ reactivity with reservoir formation minerals through injectivities. CCS is the last stage in the carbon capture and storage (CCS) cycle and is accomplished chiefly via oceanic and subterranean geological sequestration, as well as mineral carbonation. The injection of supercritical CO₂ into geological formations disrupts the sub-surface's existing physical and chemical conditions; changes can occur in the pore fluid pressure, temperature state, chemical reactivity, and stress distribution of the reservoir rock. This paper aims at advancing our current knowledge in CO₂ injection and storage systems, particularly CO₂ storage methods and the challenges encountered during the implementation of each method and analyses on how key uncertainties in CCS can be reduced. CCS sites are essentially unified systems; yet, given the scientific context, these storage systems are typically split during scientific investigations based on the physics and spatial scales involved. Separating the physics by using the chosen system as a boundary condition is a strategy that works effectively for a wide variety of physical applications. Unfortunately, the separation technique does not accurately capture the behaviour of the larger important system in the case of water and gas flow in porous media. This is due to the complexity of geological subsurface systems, which prevents the approach from being able to effectively capture the behaviour of the larger relevant system. This consequently gives rise to different CCS technology with different applications, costs and social and environmental impacts. The findings of this study can help improve the ability to select a suitable CCS application method and can further improve the efficiency of greenhouse gas emissions and their environmental impact, promoting the process sustainability and helping to tackle some of the most important issues that human being is currently accounting global climate change. Though this technology has already had large-scale development for the last decade, some issues and uncertainties are identified. Special attention was focused on the basic findings achieved in CO₂ storage operational projects to date. The study has demonstrated that though a number of CCS technologies have been researched and implemented to date, choosing a suitable and acceptable CCS technology is still daunting in terms of its technological application, cost effectiveness and socio-environmental acceptance.



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1. Introduction

Previous studies have emphasised anthropogenic CO₂ 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., [1]). The reports published by IEA 2016 and NASA

2017 confirmed that CO₂ 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 20cm increase in the 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 special report [2]). 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 (IEA [3]) (ECF [4]).

Power plants and other energy-intensive sectors are regarded as significant CO₂ emitters and are required to reduce their produced CO₂ 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. This resulted in a significant decrease in coal pricing, which in turn resulted in a greater proclivity for coal-based power generation (Hanak et al., [5]). Therefore, de-carbonisation 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 decarbonising 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 CO₂ 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 [6] the critical criteria of a viable CO₂ storage option are net CO₂ emission reduction, high storage capacity, long-term CO₂ 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 et al., [7]).

Several reviews, including Bachu [8] and Bai et al. [9] have addressed various features of CO₂ storage in the past. However, particular areas have yet to be addressed or thoroughly examined. Although CO₂ storage is a technically established technique, further deployment is hampered by ambiguity and challenges related to estimating storage capacity, tracking verification and monitoring of CO₂ during and after injection, characterising potential injection-induced seismicity, standardising storage evaluation criteria, and practical and ethical mechanisms. Furthermore, CO₂ 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 CO₂. These options include underground geological storage, deep ocean storage, and mineral carbonation (IPCC Special Report, [2]). Underground geological storage, in particular, encompasses several subcategories, such as saline aquifers, depleted oil and gas reservoirs, un-mineable coal seams, hydrate storage, and CO₂ storage within enhanced geothermal systems (Na J, et al., [10]).

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 decarbonisation in the manufacturing and energy sectors (GCCSL, [11]). 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, [12]). The final stage in the CCS process involves the long-term containment of CO₂. This can

be accomplished through several methods, such as mineral carbonation, oceanic storage, and underground geological storage. The latter includes storing CO₂ in saline aquifers, depleted oil and gas reservoirs, un-mineable coal seams, and other geological formations. The primary attributes of a viable CO₂ storage solution encompass a net decrease in CO₂ emissions, substantial storage capacity, extended isolation of CO₂ for a minimum of several centuries, cost-effectiveness and minimal energy penalty, as well as mitigated environmental consequences (Yamasaki, [6]). However, the acceptance and adoption of the technology by the general population is another crucial component that can have a substantial impact on its implementation (Mabon and Shackley, [7]).

Multiple scholarly articles have examined many facets of CO₂ storage (Bachu, [13]), as indicated in Appendix A, Table A1. Nevertheless, certain aspects have not yet been addressed or thoroughly examined. Although CO₂ 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 CO₂ 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 CO₂ storage is rapidly advancing, necessitating a comprehensive examination and discourse on recent advancements and developments.

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

2. CO₂ Sequestration Methods

According to the IPCC Special Report from 2005, different CO₂ sequestration methods that could be used for stored CO₂ include deep ocean, geological and mineral carbonation, and several subterranean reservoir formations alternatives do exist, including saline aquifers, depleted oil and gas reserves, unreachable coal seams, hydrate storage, and CO₂ inside improved geothermal systems (Bachu et al., [14]), (Han and Winston Ho [15]).

Figure 1 and Appendix A presents a comprehensive review of significant large-scale CSS initiatives that have been implemented globally. In the majority of these operations, CO₂ 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 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 and site accessibility (particularly relevant to ocean and mineral sequestration), as well as concerns related to the security of stored CO₂ 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.

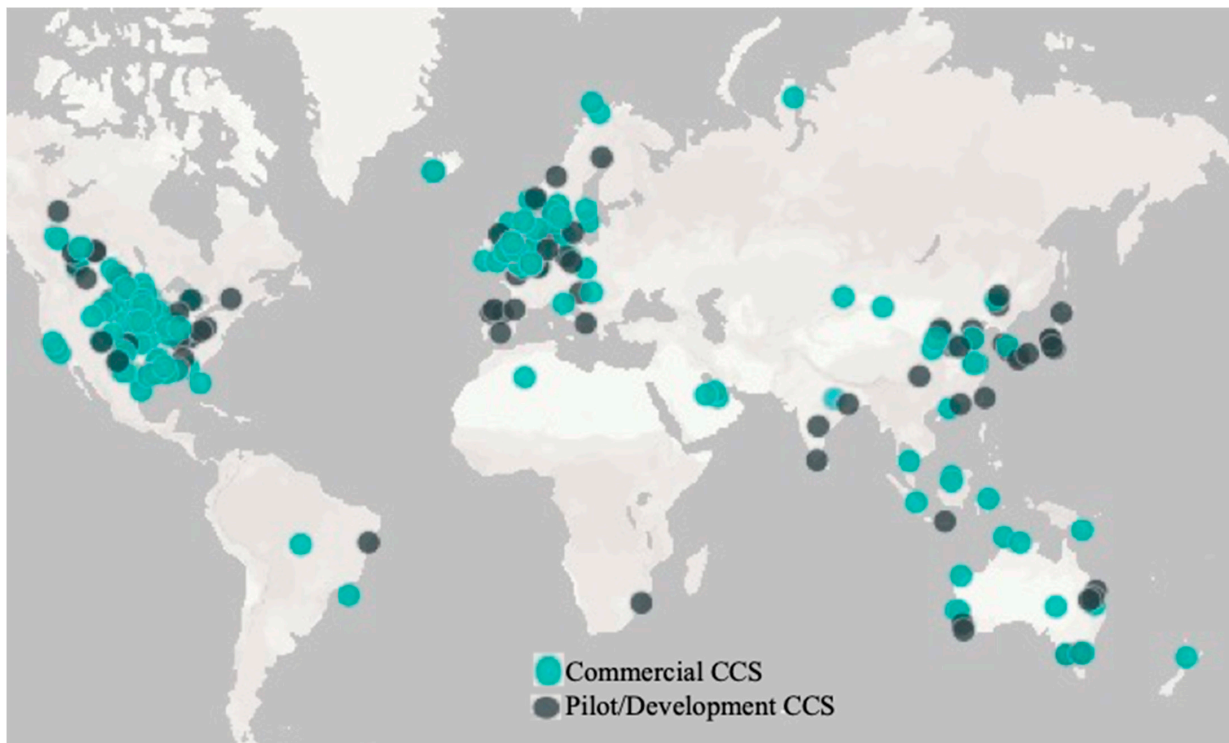


Figure 1. Worldwide CCS initiatives encompassing large-scale commercial projects that have been previously operational and pilot development operations (MIT, [16]; Shukla et al., [17]; Global CCS Institute-CO₂RE).

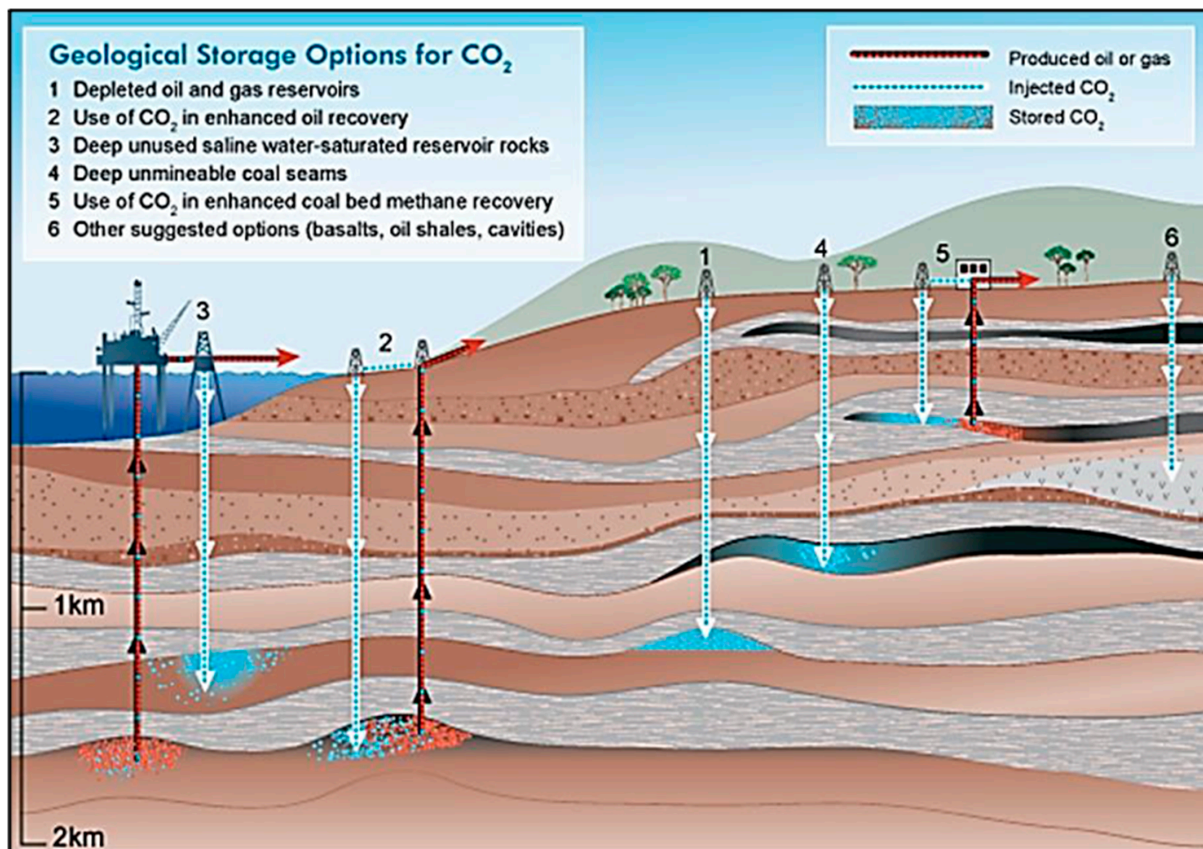


Figure 2. Schematic illustration of various geological storage systems for CO₂ (courtesy CO₂CRC, [18]).

3. Storage in Subsurface Reservoir Formations

The most workable sequestration option is an underground geological storage system. The security of the CO₂ being stored, as well as the detrimental effects on the ecosystem, are some of the key points that set geological storage from CO₂ mineralisation and marine storage. Figure 2 depicts various possible geological storage systems that are considered to be effective and would need further investigation to be better understood.

Considering that available information in the overwhelming CSS can be 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.

3.1. Brine Aquifers

Several researchers have acknowledged that storing CO₂ in deep salty aquifers represents one of the most successful strategies for reducing CO₂ in the atmosphere (Li et al., [19]) (Javaheri et al., [20]), (Yang et al., [21]), (Frerichs et al., [22]), and (Burnol et al., [23]), due to its already available technological and significant possible storage capacity, (Bachu et al., [14]). However, most saline aquifers are presently unsuitable for other synergistic or competing uses (Trémosa et al., [24]), especially in highly populated nations (Procesi et al., [25]; Quattrocchi et al., [26]). The absence of facilities including wells for CO₂ injection, surface handling equipment, and transportation pipeline networks makes many salty aquifers less desirable as potential storage reservoir formation alternatives at present (Li et al., [27]).

Recently, the topic of discussion has been the potential for CO₂ to be stored in salty aquifers (Bachu et al., [28]), (Wei et al., [29]) in combination with EOR storage (Boundary-Dam-Apache). These studies address topics including site description and long-term planning according to Bachu [28] as well as the range of complementary and competing subterranean uses (Procesi et al., [25]).

Because of their vast pore volume and high permeability, aquifer reservoir formations can hold massive amounts of CO₂, cutting down on an overall number of CO₂ injection wells required and easing pressure dissipation (Shukla et al., [17]). Upon flowing into the storage reservoir formation, supercritical CO₂ 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., [30]) (Cantucci et al., [31]). Mineral formation and dissolution may alter rock porosity and, as a result, the capacity of the storage reservoir (Wdowin [32]).

Previous studies (Tapia et al., [33]) have shown that supercritical CO₂ has a density of approximately 0.6–0.7 g/cm³ in saline reservoirs; the low density can influence the uprise movement of CO₂ towards the cap-rock because of buoyancy forces due to density variation.

According to previous studies (Armitage et al., [34]), a large aquifer storage basin with a high sealing capacity of the cap-rock is necessary for long-term and stable CO₂ storage. 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 CO₂ migration from the storage deposit below. With its low permeability, cap-rock is crucial for preventing CO₂ from escaping the retention reservoir and minimising leakage. Another essential element that may result in cap-rock integrity loss and CO₂ leakage is the existence of unrecognised fracturing and fault planes. However, as revealed by the review, no previous researchers have investigated the impacts of CO₂–brine reactivity on injectivity and the fracturing network and fault plane for CO₂ 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., [35]).

Stratigraphical and/or Structural Trapping: When CO₂ is introduced into a geological formation, it may move to the top and get trapped behind an impermeable top seal (Kim et al., [36]), 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 in Figure 3a above. This is the most common kind of subsurface trapping system.

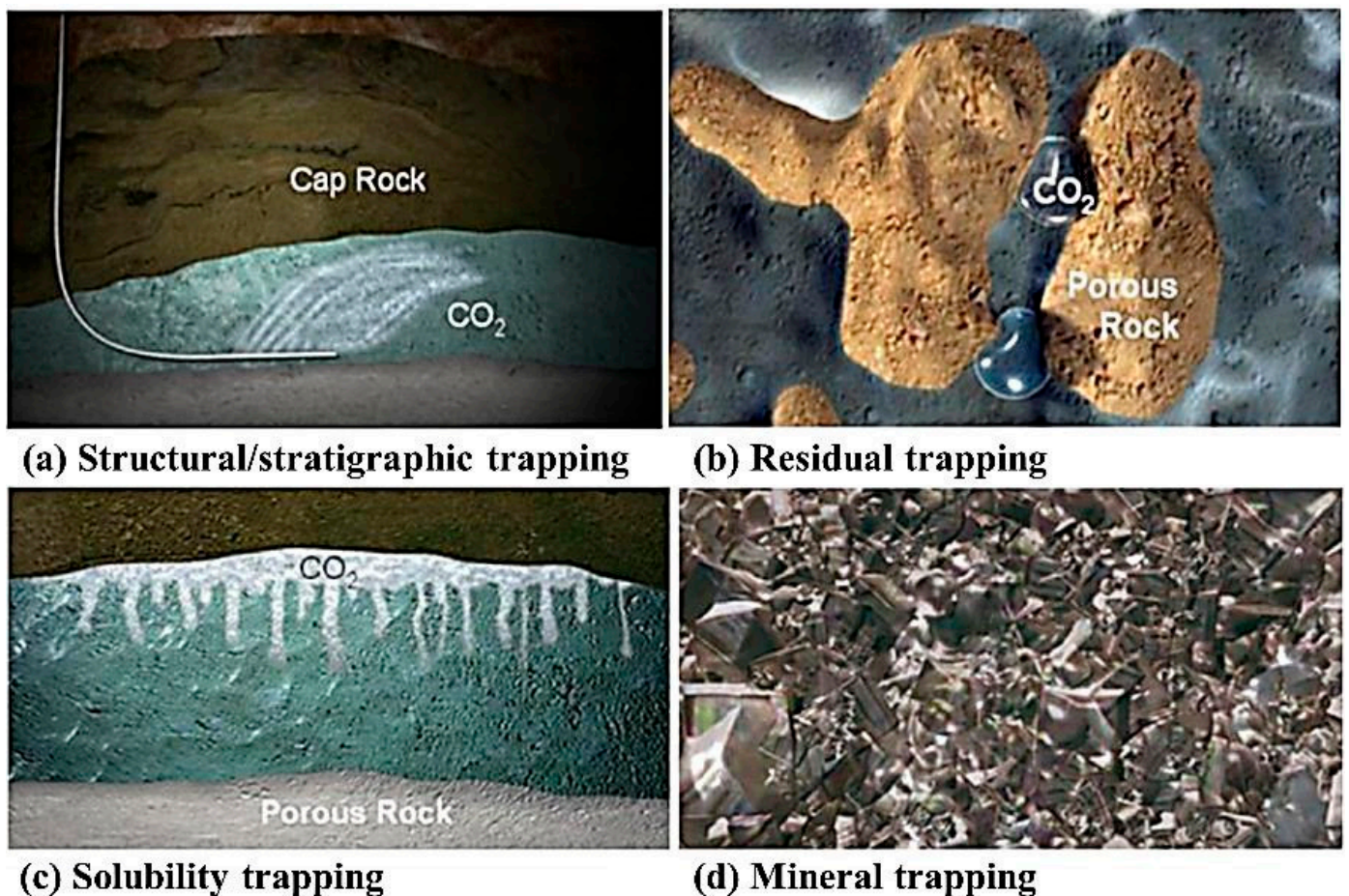


Figure 3. Illustration of the four major CO₂-trapping subsurface systems (Zhao et al., [37]). The four major trapping processes that may safely handle CO₂ storage are as follows: (a) structural/stratigraphic trapping, (b) residual trapping, (c) solubility trapping, and (d) mineral trapping.

CO₂ Rock Pores Capturing: Injection of CO₂ into aquifer porous rock gives rise to fluid displacement due to differences in density. Figure 3b above shows how the fluid displaced by the CO₂ flows, returns, disconnects, and traps the remaining CO₂ within pore spaces. It has been observed that the method occurs exclusively when water drainage processes occur during CO₂ injection, rather than inside structural and stratigraphic traps (Bachu et al., [13]).

Solubility trapping: CO₂ dissolves in brine through the chemical process of solubility, plummeting the quantity of CO₂ gas-phase (Figure 3c). The density of brine is increased by the solubility of CO₂, and this may cause gravitational instability, hastening the transition of injected CO₂ to CO₂-lean brine (Kneafsey et al., [38]).

Trapping due to Mineral: CO₂ 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 CO₂ in an inert lesser phase across a specific subsurface geological timeframe, as demonstrated in Figure 3d above (Bachu [14]). It is a more gradual process than the solubility capturing that takes place over a longer geologic period (Gunter et al., [39]) (Sundal et al., [40]).

Although a number of studies have argued that storing CO₂ in salty aquifers would be more effective than storing CO₂ 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 CO₂ for storage as well as EOR. As a consequence, it is possible that storing CO₂ in hydrocarbon formations is better than storing it in saltwater aquifers.

3.2. Drained Hydrocarbon Reservoir Formations

The sequestration of CO₂ in depleted oil and gas reservoirs is widely recognised as one of the most efficient techniques of CO₂ storage. Among these advantages are the following: (a) drained hydrocarbon reservoirs have been the subject of substantial research both before and during the hydrocarbon exploration period, including research about their storage capacity; (b) both onshore and offshore infrastructural facilities, existing infrastructure, including CO₂ injection wells and transportation, may be used with little modification for the storage process (Sigman et al., [41]); (c) if this was not the case, CO₂ gas injection to enhance oil recovery would have been less attractive and abandoned many years ago. Suitable hydrocarbon field data as an analogue may be utilised for illustrating the efficacy of cap-rock across a geologic timeframe to strengthen oil and gas reservoirs (Heinemann et al., [42]).

Reservoir rocks and brine properties are similar and commonly found in both hydrocarbon reservoirs and deep aquifer storage systems (Li et al., [19]). Oil and gas reservoirs, on the other hand, may be considered for EOR, making them more economically advantageous than saline aquifers (Zangeneh et al., [43]) (Gao et al., [44]). Because the worldwide average recovery factor from a typical oilfield is about 40% (BGS, [45]), usually, many barrels of oil are still in the hydrocarbon reservoirs. This is 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 (CO₂, 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. CO₂ injection seems to be the optimal choice because it may reduce oil viscosity and is less expensive than liquefied natural gas (Jaramillo et al., [46]). More CO₂ for improved oil recovery is anticipated to be accessible from vital gathering point sources with the introduction of CCS technology (IPCC Special Report [47]). It has been claimed, for example, that the use of CO₂ for EOR has resulted in an increased output of about 260,000bopd in the U.S.A. (GCCSI [11]).

The International Energy Agency (IEA) [2] set out the following as the primary criteria for the implementation of CO₂ oil recovery support (EOR) projects:

- a. Additional site characterisation involves investigating potential leakage risks, such as the condition of the cap rock and any abandoned wells with integrity problems;
- b. Additional evaluations of surface processing plants' fugitive and discharging emissions;
- c. 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 CO₂-EOR and CO₂ permanent storage fall under two distinct regulatory umbrellas; the former focuses on resource recovery whereas the latter is concerned with waste management Marston [48]. 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 CO₂-EOR project is initiated involves the kind and number of contaminants in CO₂ streams. Depending on the CO₂ source and the accompanying collecting procedures, a variety of contaminants might be contained as part of the CO₂ injection fluid (Porter et al., [49]). The permissible impurities and concentrations are determined by a mix of transit, storage, and economic factors. CO₂ streams must meet a minimum purity standard of roughly 90%vol (Jarrell et al., [50]). In the case of CO₂, 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 CO₂ in a higher concentration. It has also been established that non-condensable contaminants lower the CO₂ storage capacity by a factor that is larger as compared to the mole percentage of contaminants present in the CO₂ injection system (IEAGHG [51]).

The most typical issue connected to contaminants is corrosion. Due to the corrosive effects that impurities (such as SO₂, NO₂, CO, H₂S, 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., [49]). It is important to note that even though certain impurities such as CO, H₂S, and CH₄ 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 CO₂ injection stream will be combustible due to the low quantities of the impurities in question. Another issue that may influence the effectiveness of the CO₂-EOR process is an excessive concentration of O₂ in CO₂ streams. The presence of O₂ in the reservoir may stimulate microbial activity (Porter et al., [49]), which can ultimately lead to operational problems such as injection obstruction, oil deterioration and oil souring.

Previous studies (Igunnu et al., [52]) have connected environmental problems of EOR with volumes of water production that may include radioactive compounds and dangerous heavy metallic substances. If an appropriate waste management and disposal strategy is not 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 [53] provided evidence to show that the Weyburn-Midale CO₂ storage project in Canada is an example of how, collected in the Weyburn oilfield, CO₂ 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, [54]). According to Zaluski et al. [55] and Verdon [56], long-term surveillance can enable seismicity evaluation of CO₂'s impact on the reservoir and the fluids' mutual effect; oil and minerals have been the primary focuses of CO₂-EOR research (Hutcheon et al., [57]). The Weyburn case history inspired (Cantucci et al., [31]) to study the geochemical equilibrium between brine and oil and develop a biogeochemical model for CO₂ storage in underground reservoirs. A hundred years into the future, they predicted precipitation and disintegration processes based on research into reservoir formation during CO₂ 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 CO₂ and the dissolution of carbonate. Furthermore, the development of chemical characteristics over time indicated that CO₂ might be securely stored via mineral and solubility trapping.

Perera [58] acknowledges that though the CO₂-EOR method has substantially improved oil recoveries, further improvement is needed using the following strategies: (a) using numerical evidence, Tenasaka [59] proved that this was possible within the normal range of CO₂ injection. In the San Joaquin basin, scientists injected around 2.0HCPV (hydrocarbon pore volume) of CO₂ 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 [59] demonstrated that there was a greater recovery of oil using his numerical methodology; (b) using better and innovative CO₂ flooding design and well management can positively

influence more oil recovery from the reservoir; and (c) increasing the mobility ratio by raising water's viscosity (Thomas [54]). Kuuskraa [60] presented a method for minimising miscibility pressure using miscibility-enhancing agents.

3.3. In-Accessible Coal Seams

An additional option for sequestering human-caused CO₂ 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 CO₂ in the gas phase than methane, and this is the basis for the CO₂ trapping process. According to Shukla [17], this means that the methane output could be increased while the CO₂ was permanently stored. Thus, large amounts of CO₂ may be stored while commercial unconventional shale methane (CBM) processes are made more productive and profitable (Krooss et al., [61]) (Gilliland et al., [62]). It should be underlined that although CO₂ increases CBM synthesis, the overall quantity of methane generated is not always higher than without the addition of CO₂. The International Energy Agency Working Group on Greenhouse Gases IEAGHG [51] provided an overview of the essential technical parameters needed for the effective implementation of enhanced coal seam production, which include (a) the homogeneity reservoir; (b) threshold of fractures and fault planes; (c) upper depth limit; (d) coal geomorphology; and (e) permeability adequacy.

Two experimental locations, the Alberta Carbon Trunk Line (ACTL) in Canada and the San Juan Basin pilot in the United States, have reportedly used the ECBM approach. The conclusions of the evaluations for the Alberta project (Krooss et al., [61]) were as follows: (a) even in constrained reservoirs, continuous CO₂ injection is feasible; (b) injection may be performed notwithstanding a decrease in injectivity; (c) significantly enhanced CBM production is expected; (d) the injected carbon dioxide stays in the reservoir, boosting sweep efficiency Lakeman [63].

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 carried out 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., [62]). 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 CO₂ EOR has been used successfully for years in the upstream oil and gas sector, the utilisation of CO₂ 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 CO₂ EOR process works could help alleviate some of those worries. For example, the creation of technically recoverable shale in ECBM could require 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.

3.4. Subsurface Basalt Formations

There exists a considerable body of literature on subsurface basalt deposits within central igneous provinces, and many researchers (McGrail et al., [64]) (Pollyea et al., [65]) (Matter et al., [66]) have suggested subsurface basalt deposits as a possible CO₂ 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 CO₂ storage capacity (Anthonsen et al., [67]). One of the most important advantages of such rocks' potential to store CO₂ is that their physical and chemical characteristics, as well as the amount of divalent metal ions they contain, may fix CO₂ during past geological periods (Van Pham et al., [68]). The 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 rubble zones between separate flows are the most critical portions of a basalt sequence for CO₂ storage.

Complimentary CO₂ injected into subsurface basalts (the CarbFix pilot scheme, Iceland) may replace water in the rock's pore spaces and cracks (Matter et al., [66]). The decrease in water content may impede basalt carbonation and hydration. Therefore, it may be possible to inject CO₂ and the right amount of water into the same reservoir based on the following points: (a) because it offers sufficient depth, denser CO₂ liquid may sink, which delays the release of CO₂ back into the atmosphere; (b) it makes it possible to form stable carbonates in a shorter amount of time than would normally be required by geologic processes; (c) it prevents acidic basement fluids from rising via an impervious sediment layer; (d) it can be converted into a stable hydrate; (e) it is essential to remember that a small quantity of CO₂ leaking does not inevitably damage the sea bottom ecosystems.

Because of the anticipated development of dolomitic carbonate minerals, with the possibility of CO₂ being trapped in basalts for thousands of years, 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., [68]). These researchers found that, at 40 degrees Celsius, 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 and 100 degrees Celsius. In addition, they found that the carbonation and hydration processes both increased solid volume and inhibited pore access, decreasing the maximum quantity of CO₂ 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 CO₂ storage for the future utilising basic magnesium silicates. In serpentinites, rocks that are both plentiful and thermodynamically suitable for the production of magnesium carbonates, CO₂ combines with magnesium silicates to produce magnesium carbonates Seifritz [69]. Andreani et al. [70] 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.

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 CO₂ storage. However, CO₂ seeping via fissures has the potential to mineralise and be trapped inside the formation, delaying its escape to the surface (IEAGHG [51]). As such, further research is required to characterise the kinetics of CO₂-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 CO₂ migration in the presence of likely fault plane fractures.

3.5. CO₂ Sequestration in Hydrate Deep Formations

Previous studies (Nobre et al. [71]) have shown that subsurface CO₂ storage systems as hydrates represent another potential, modern strategy that uses a lattice of water molecules to capture CO₂ molecules. When water and the right level of pressure and temperature

are present, CO₂ hydrate may form rapidly (Circone et al., [72]). 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 CO₂ hydrate might have applications in both underground geology and the storage of CO₂ 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. [73]), 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 is possible that there is a lack of sufficient space for a CO₂ collection plant.

The process of the CO₂ hydrate storage mechanism involves buoyancy and drives the migration of liquid CO₂, which is capped by a developing impermeable CO₂ hydrate cap (Figure 4). The CO₂ hydrate equilibrium zone is lowered by injecting liquid carbon dioxide into deep water or sub-permafrost sediments (Rochelle et al., [73]). As more liquid CO₂ moves into the colder hydrate stable zone, a layer of impenetrable CO₂ hydrates builds inside the pore holes of the sedimentary reservoir rock. The US Department of Energy (DOE), on the other hand, proposed a CO₂-EGR-based hydrate storage technology (enhanced gas recovery). CO₂ is injected into sediments that contain methane hydrates, releasing the methane from the hydrates and forming CO₂ hydrates in its place (Burnol et al., [23]). Because CO₂-EGR is still a novel idea, research into its effectiveness has been limited so far. According to Oldenburg [74], one of the primary issues is the use of methane, which might in turn react with the injected CO₂ in an enhanced gas cycle, resulting in the gas resources being depleted.

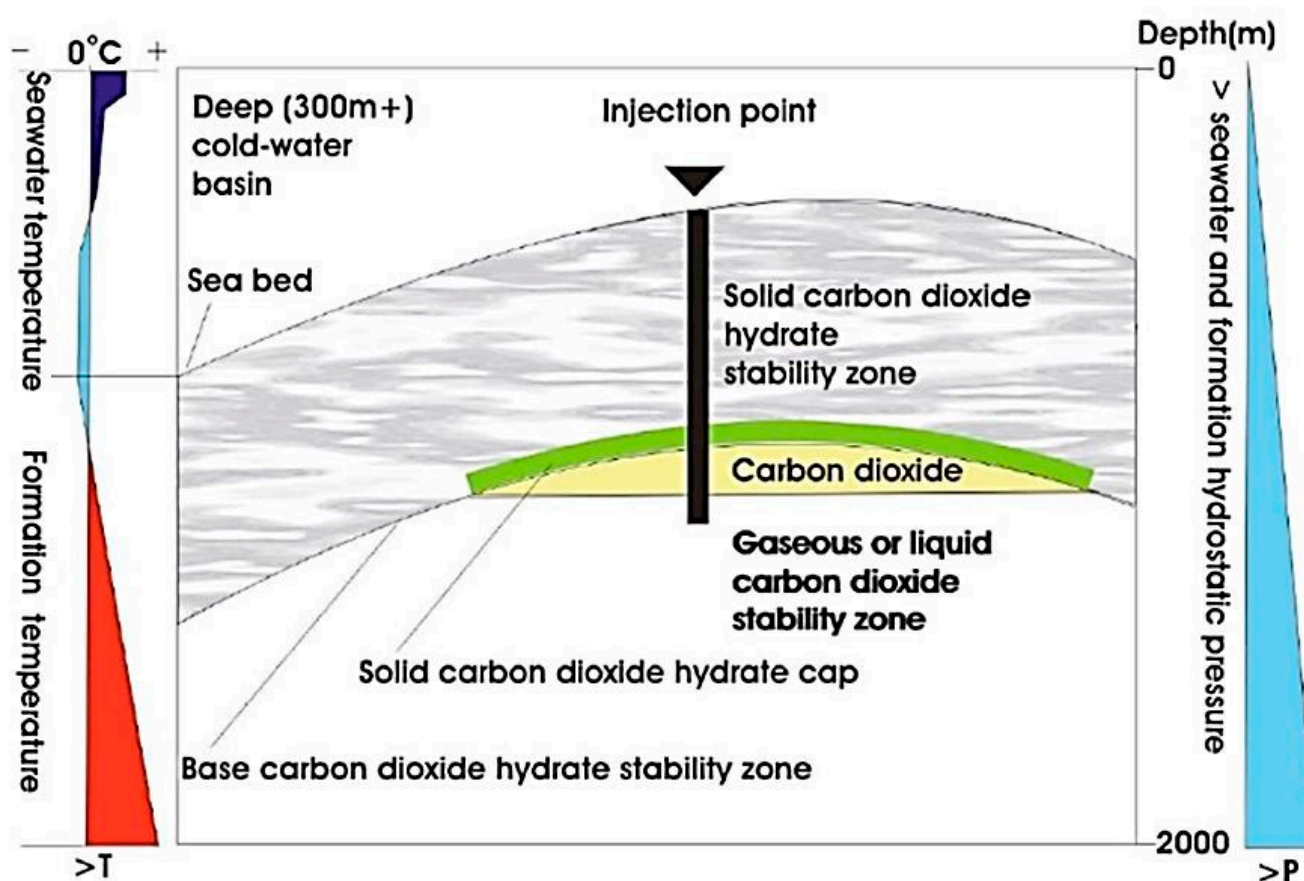


Figure 4. Diagram illustrating hydrate formation sequestration with its CO₂ hydrate seal (Rochelle et al., [73]).

Presently, the technology required to store CO₂ in hydrates is not very advanced, with most researchers (Jemai et al., [75]) (Talaghat et al., [76]) focusing on theoretical modelling and lab-scale experiments (Ghavipour et al., [77]) (Ruffine et al., [78]) (Rehder

et al., [79]). For this reason, there are still a number of challenges to be solved, especially with CO₂-EGR. However, local temperature and pressure fluctuations caused by drilling through hydrate-bearing sediments may destabilise the hydrate formation in its entirety (Khabibullin et al., [80]). How the CO₂-CH₄ hydrate exchange mechanism affects methane production and how to characterise the hydrate cap development may constitute the major outstanding problems that need to be solved to improve the evaluation of hydrate storage viability.

3.6. Enhanced Geothermal Systems Based on CO₂

Previous studies (Garapati et al., [81]) and Pruess, [82] have emphasised that dense-phase CO₂, 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, CO₂ may be utilised in the process of geothermal energy by extracting heat from the ground. CO₂ can efficiently reach the rock mass due to its low viscosity and may be considered a medium for enhanced geothermal systems' operating fluid Pruess [82]. Enhanced geothermal systems that use water as the heat transmission fluid suffer from the 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 CO₂, this would make underground geological storage of CO₂ possible, which might have further benefits.

It is essential for the effectiveness of CO₂-EGS storage that the rock mass loaded with CO₂ 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 CO₂ and heavy centre of EGS with the brine-rich outside. Only countries with 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.

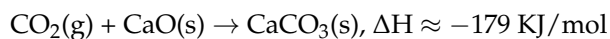
The technique is still in its early stages of technology readiness (TRL), with most research so far focused on theoretical modelling (Plaksina et al., [83]) and small-scale laboratory experiments. The main challenge to this method's development is the lack of clarity about the efficiency of closing off the area surrounding the CO₂ source. To top it all off, nothing is known about the interactions between CO₂ and rocks at high temperatures. Understanding how CO₂ affects dissolution and precipitation, and how that affects changes in fracture permeability and EGS functioning, requires further study.

4. Carbonation of Mineral

Seifritz [69], was the first person to suggest the idea of CO₂ carbonation happening in the mineral as an alternative CO₂ sequestration method. The collected CO₂ 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 via the reaction of CO₂.

Incorporation of CO₂ into minerals may be accomplished in two ways: both in and out of place. The in-place technique includes injecting CO₂ 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., [84]). 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., [85]). The in situ mineral carbonation technique has significant benefits since it does not need substantial mining and requires 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.





Geochemical processes may also 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., [86]) (Lim et al., [87]). 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., [88]). 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., [86]). 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 [89]; (Bobicki et al., [86]). When looking at the feasibility of long-term mineral carbonation that allows for the underground sequestration of carbon dioxide, Matter et al., [66] 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 mineralisation. 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 Special Report [47]).

Two of the most common alkali and alkaline-earth metal oxides, magnesium oxide (MgO) and calcium oxide (CaO), do not 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. [90] and Bruni et al. [91] 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., [90]). 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 et al., in [91], 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 whether CO_2 sequestration is possible in the near and far future by dissolving serpentinite and then precipitating calcite. This was carried out 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. The 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 (Peletiri et al., [92]). to a processing facility that receives a concentrated stream of CO₂ from a capture plant (Figure 5). A comprehensive review of capture technologies was given elsewhere by Kheirinik et al. [93]). 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 CO₂, 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 CO₂ 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 USD/tCO₂ net mineralised, accounting for CO₂ capture and transportation expenses, while also considering the supplementary energy demands.

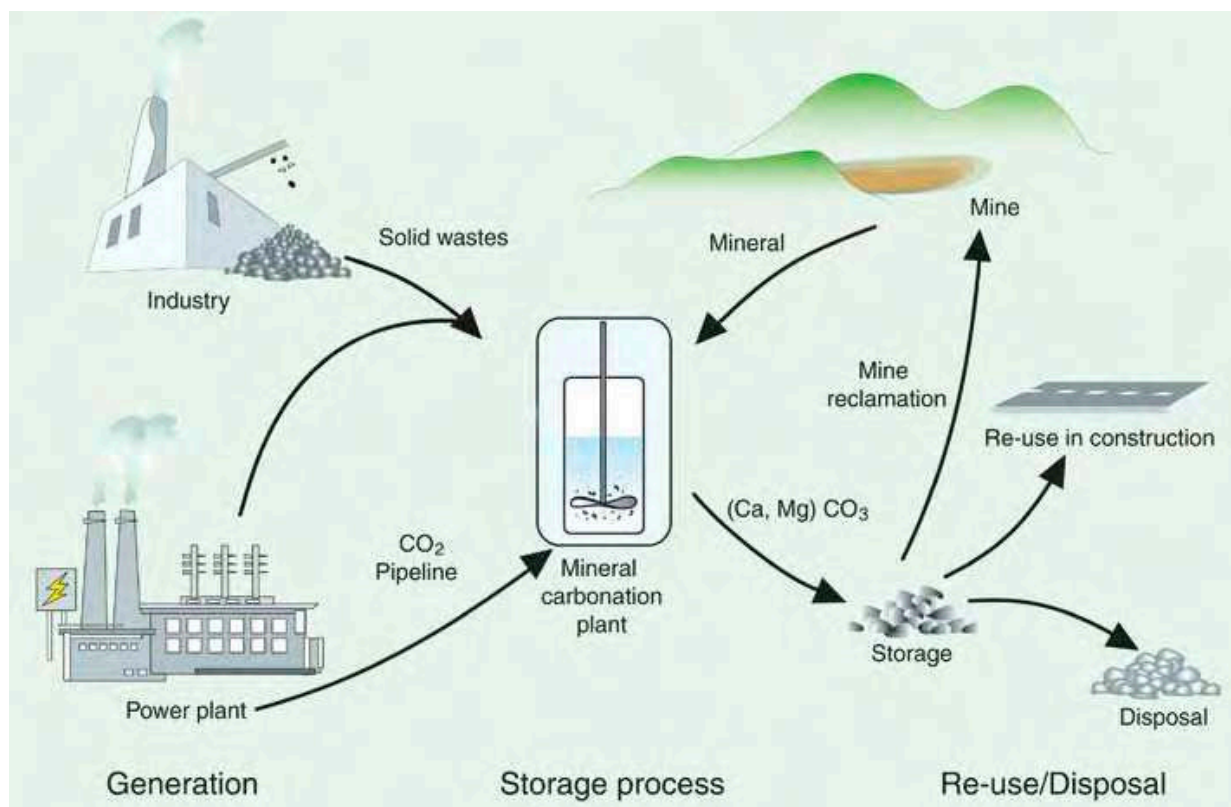


Figure 5. Illustration of the material fluxes and processes that are involved in the mineral carbonation of silicate rocks or industrial residues (W. Huijgen et al., [94]).

The mineral carbonation process necessitates the extraction of about 1.6 to 3.7 tonnes of silicates per tonne of CO₂ and results in the disposal of 2.6 to 4.7 tonnes of materials per tonne of CO₂ stored as carbonates. Consequently, the 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 CO₂ 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 pertains to the potential of industrial utilisation of CO₂ to yield a net decrease in CO₂ emissions on a comprehensive scale, through the substitution of alternative industrial processes or products. Accurate evaluation of the CO₂ 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 CO₂. 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 CO₂ kept, the modest quantities utilised, and the potential for substitution resulting in elevated CO₂ emissions, it may be deduced that the impact of industrial applications of captured CO₂ 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 Special Report [47]). Accordingly, future research should concentrate on (a) the potential for less terrain change; (b) mineral carbonation in terms of mineral and CO₂ dissolution; (c) material stratum diffusion; and (d) managing mineral impurities throughout the sequestration process.

5. CO₂ Sequestration on Ocean Floor

Intentionally injecting CO₂ into the deep ocean floor is another option for anthropogenic CO₂ sequestration IPCC [47]. The oceans cover around 70% of the planet. In the industrial era, they sucked up over a third of all man-made CO₂ emissions from the atmosphere and had an average depth of 3.8 km (Adams et al., [95]) (Tanhua et al., [96]). Mathematical simulations have indicated that injected CO₂ 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 CO₂ into the water column, typically below 1000 m, using a fixed pipeline or a floating ship; or the deposition of CO₂ onto the sea floor at depths below 3000 m, using a fixed pipeline or an offshore platform. In the latter method, CO₂, 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.

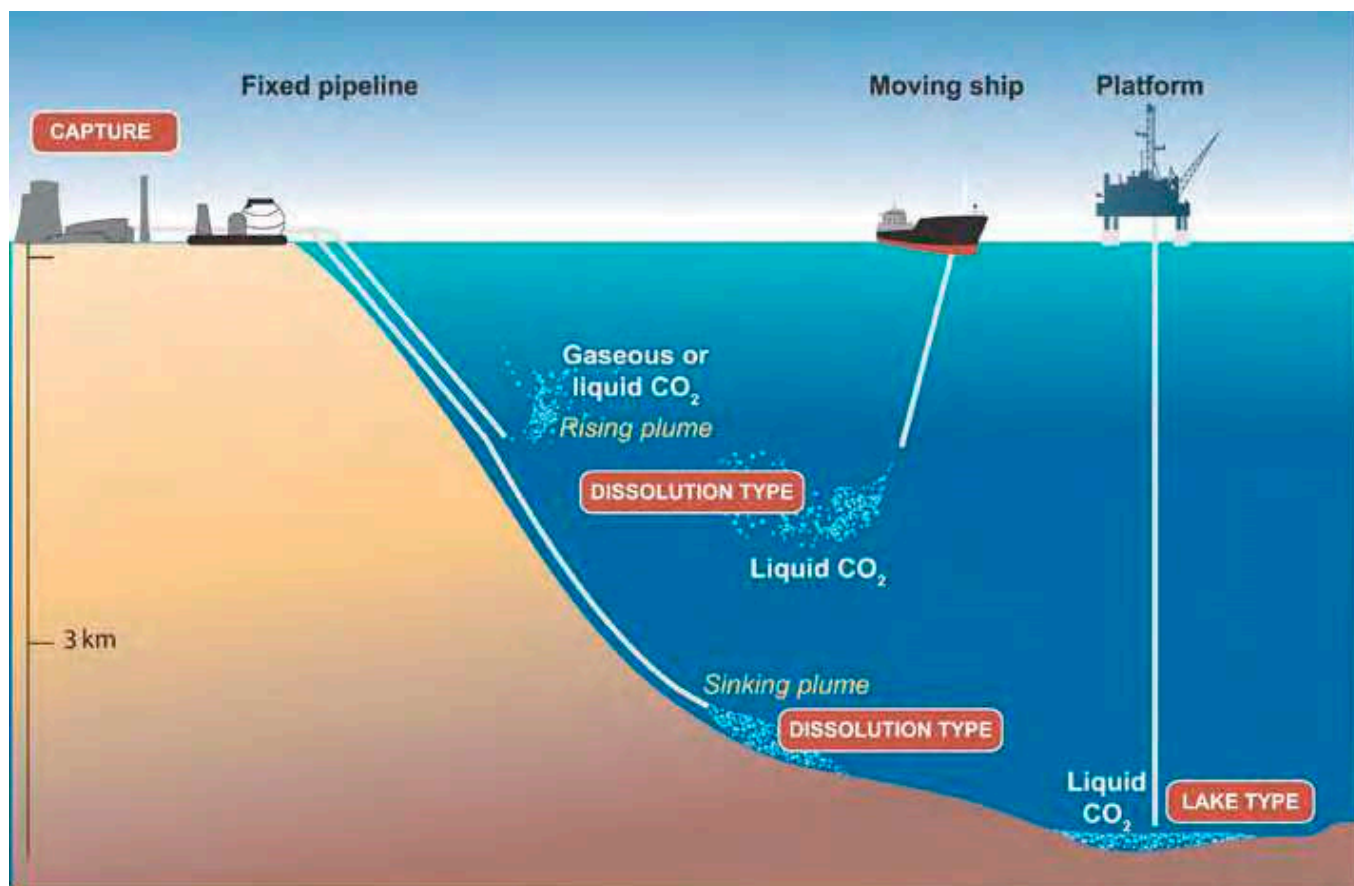


Figure 6. An illustration of many concepts related to the storage of CO₂ in the ocean. The process of ocean storage can be classified into two types: dissolution type and lake type. In the dissolution type, CO₂ undergoes rapid dissolution in ocean water. On the other hand, in the lake type, CO₂ exists initially as a liquid on the sea floor (CO₂CRC [18]).

Direct CO₂ dissolution into seawater is the principal technique that could be used in ocean storage. The first involves releasing CO₂ directly into the ocean floor, where it will form droplet plumes that will rise into the air. As an alternate method, liquid CO₂ 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., [95]). Since there is a potential for localised acidification of water from the sea in the vicinity of CO₂ injection location, the storage of CO₂ 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 (Hofmann et al. [97]). Furthermore, it is unclear if international laws will permit CO₂ 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. [71]). Therefore, it is prohibited to dump CO₂ into the ocean if it is considered industrial waste. Although CO₂ was added to the “reverse list” in the London Protocol modification that allowed for the storage of CO₂ beneath the seabed in 2006, there is still no agreement on whether or not CO₂ should be classified as industrial waste. “CO₂ 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 (Anon [98]) (ZeroCO₂ [99]). 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 CO₂ concentration allocation. Xu et al. [100] constructed a regional ocean general circulation model that assumed there was no air-to-sea CO₂ exchange and investigated the prospect for CO₂ 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 CO₂ 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 CO₂ into the water over a few hundred years.

Following fifty years of constant injection of CO₂, more than ten percent of the dissolved CO₂ would be released back into the environment. This leakage should be considered as a major concern. In 2004, Adcroft et al. used an ocean circulation model to assess the storage efficiency of impulse injections based on mean residence time. CO₂ 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 the impact of air–sea CO₂ 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 CO₂ concentration after injection might be considered. A place where CO₂ is adequately diluted while having little environmental impact is preferable. However, by simulating CO₂ injection into a number of models of the ocean's main circulation at several sites around Japan, the spatial variability of CO₂ content concerning the injection rate and eddy activity distribution has been studied (Masuda et al., [101]). These researchers used an ocean general circulation model to perform their research. Specifically, the data indicated that the highest CO₂ concentration may vary by a factor of 10 across places, where the principal driver of this variation is the regionalisation 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 research 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 CO₂ 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 include the following: (a) 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; (b) biological and ecological factors—investigations pertaining to the impact of increased CO₂ levels on biological systems inside the deep sea, encompassing investigations of greater duration and larger size than those previously conducted; (c) 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 CO₂ from a fixed pipe or ship, as well as carbonate-neutralisation approaches. These assessments are carried out in situ, on a small scale, and on an ongoing basis; (d) finally, the future focus should be on the advancement of methodologies and sensor technologies to detect CO₂ plumes, as well as understanding their ecological and geochemical impacts.

6. Conclusions and Outlook

This paper provides a comprehensive review of the current advancements in CO₂ sequestration with special interest in geological CO₂ storage. This highlights significant steps that have been covered so far, as well as obstacles that still need to be addressed for geological subsurface CO₂ sequestration, and approaches adopted in calculating CO₂ storage capacity.

Even though CO₂ sequestration by storage in the ocean and storage through the process of carbonation has been established, CSS remains the most viable practical alternative because of financial concerns, vast geographical dispersal, and environmental difficulties. This is the case because it has been proven that CO₂ can be sequestered.

Mineral CO₂ 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 CO₂ 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 CO₂ sequestration has the potential to evolve into a viable technology for employment, forming an integral component of a diverse range of CO₂-reducing technologies. It is crucial to use each technology in its most suitable context within a comprehensive portfolio. The field of mineral CO₂ 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 CO₂ sequestration and its substantial potential for sequestration, justifies the need for additional investigation into mineral CO₂ sequestration.

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Abbreviations

ACTL	Alberta Carbon Trunk Line
CBM	Coal Bed Methane
CCS	Carbon Capture and Storage
CO2CRC	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 A

Table A1. Worldwide CCS initiatives encompassing large-scale commercial projects that have been previously operational and pilot development operations (MIT, [16]; Shukla et al., [17]; Global CCS Institute-CO₂RE).

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 ₂ CRC 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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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
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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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
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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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
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™ 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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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
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
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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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	The Netherlands	2024	Hydrogen Production
Air Products Refinery Rotterdam CCS	Commercial CCS Facility	Advanced Development	The Netherlands	2024	Hydrogen Production
Buggenum Carbon Capture (CO ₂ Catch-up) Pilot Project	Pilot and Demonstration CCS Facility	Completed	The Netherlands	2011	Power Generation
Delta Corridor Pipeline Network	Commercial CCS Facility	Early Development	The Netherlands	2026	CO ₂ Transport and Storage
ExxonMobil Benelux Refinery CCS	Commercial CCS Facility	Advanced Development	The Netherlands	2024	Hydrogen Production
Hydrogen 2 Magnum (H2M)	Commercial CCS Facility	Early Development	The Netherlands	2024	Power Generation
K12-B CO ₂ Injection Project	Pilot and Demonstration CCS Facility	Completed	The Netherlands	2004	Natural Gas Processing
L10 Carbon Capture and Storage	Commercial CCS Facility	Early Development	The Netherlands	2026	Hydrogen Production
Porthos-Compressor Station	Commercial CCS Facility	Advanced Development	The Netherlands	2024	CO ₂ Transport and Storage
Porthos-Offshore Pipeline	Commercial CCS Facility	Advanced Development	The Netherlands	2024	CO ₂ Transport and Storage
Porthos-Onshore Pipeline	Commercial CCS Facility	Advanced Development	The Netherlands	2024	CO ₂ Transport and Storage
Porthos Storage	Commercial CCS Facility	Advanced Development	The Netherlands	2024	CO ₂ Transport and Storage
Shell Energy and Chemicals Park Rotterdam	Commercial CCS Facility	In Construction	The Netherlands	2024	Bioenergy
Yara Sluiskil	Commercial CCS Facility	Early Development	The Netherlands	2025	Fertiliser Production
Zeeland Refinery Azur	Commercial CCS Facility	Early Development	The Netherlands	2026	Hydrogen Production
Project Pouakai Hydrogen Production with CCS	Commercial CCS Facility	Early Development	New Zealand	2024	Hydrogen Production
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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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
Boryeong-KoSol Process for CO ₂ Capture (KPCC) Test	Pilot and Demonstration CCS Facility	Completed	Republic of Korea	2010	Power Generation
Hadong-Dry-sorbent CO ₂ Capture System Test	Pilot and Demonstration CCS Facility	Completed	Republic of Korea	2014	Power Generation
Korea-CCS 1 & 2	Commercial CCS Facility	Early Development	Republic of 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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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
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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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
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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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	2027–2028	Power Generation
Cane Run CCS	Commercial CCS Facility	Early Development	USA		Power Generation
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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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
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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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
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
Michigan Basin (Phase II) Geologic CO ₂ Sequestration Field Test	Pilot and Demonstration CCS Facility	Completed	USA	2008	Natural Gas Processing

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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
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

Table A1. Cont.

Facility Name	Facility Category	Facility Status	Country	Operational	Facility Industry
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
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

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