CARBON CAPTURE, UTILIZATION AND STORAGE

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OVERVIEW

Climate change is a serious issue and projected greenhouse gas (GHG) emissions present a serious concern for the environment in the near future. The Paris Agreement, adopted by the United Nations Framework Convention on Climate Change (UNFCCC) in 2015 by 196 international Parties, aims to limit global warming to well below 2°C, preferably limited to a safer 1.5°C, above pre-industrial[1] levels. To achieve this ambitious target, a global effort to stabilize and sharply reduce GHG emissions has been initiated.

The Intergovernmental Panel on Climate Change (IPCC) presented four scenarios for limiting global temperature rise to 1.5°C in their Special Report issued in 2019. All the scenarios included carbon capture and three required the involvement of major use of carbon capture. Thus, Carbon Capture and Storage (CCS) projects have recently gained renewed momentum for expanding development. In this context, the main carbon substance of concern is carbon dioxide (CO_2), produced as a byproduct of combustion.

The International Energy Agency (IEA) introduced the Sustainable Development Scenario[2], denoting a decline in global CO_2 emissions from the energy sector to net zero by 2070, inspired by the United Nations (UN) energy-related sustainable development goals for emissions, energy access and air quality. The report explicitly states that reaching net zero will be virtually impossible without CCS, and the CO_2 capturing capacity would potentially go up to around 5,635 megatonnes (Mt) in 2050, compared to current annual CO_2 capturing capacity at approximately 40 Mt. IEA projects up to 90 percent of emissions from iron and steel, cement, chemicals, fuel transformation and power generation sectors could be potentially reduced through Carbon Capture, Utilization and Storage (CCUS) by 2070.

Currently, the annual global consumption for CO_2 is around 230 Mt, mostly supplying the fertilizer industry that consumes 125 Mt per year, followed by the oil and gas industries, which consume around 70 to 80 Mt per year for Enhanced Oil Recovery (EOR). Clearly, the market demand for CO_2 in the foreseeable decades might not meet the increased captured capacity, so the energy industry is investigating ways to expand the options for CO_2 utilization and permanent storage. Injecting CO_2 into offshore depleted reservoirs has gained increasing interest. CO_2 transport for onshore and especially offshore use or storage will continue to play a critical role for global CO_2 mitigation.

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[1] Pre-industrial: The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature.

[2] The IEA's Sustainable Development Scenario (SDS) outlines a major transformation of the global energy system, showing how the world can change course to deliver on the three main energy-related SDGs simultaneously.

There are also compelling commercial demands for reducing CO_2 emissions for shipping industries to consider. Climate impact is now a measure that influences financing for shipping companies. A global framework was established in 2017 to assess and disclose the climate alignment of financial institutions' shipping portfolios. The "Poseidon Principles" apply to lenders, relevant leasers, and financial guarantors including export credit agencies. Currently, the signatories to the Poseidon Principles represent nearly 50 percent of the global ship finance portfolio at approximately $185 billion. Other financial trends also showed that the capital has moved toward lower emission asset classes which is showcased by the recent popularity of environment social governance (ESG) investment and the increase in so-called "green bonds" designed specifically to support climate-related or environmental projects.

CURRENT DEVELOPMENTS

Carbon Capture, Utilization, and Storage (CCUS) (Figure 1) outlines the process by which CO_2 can be captured, cleaned, dehydrated, liquefied, transported, and stored or utilized at a final location.

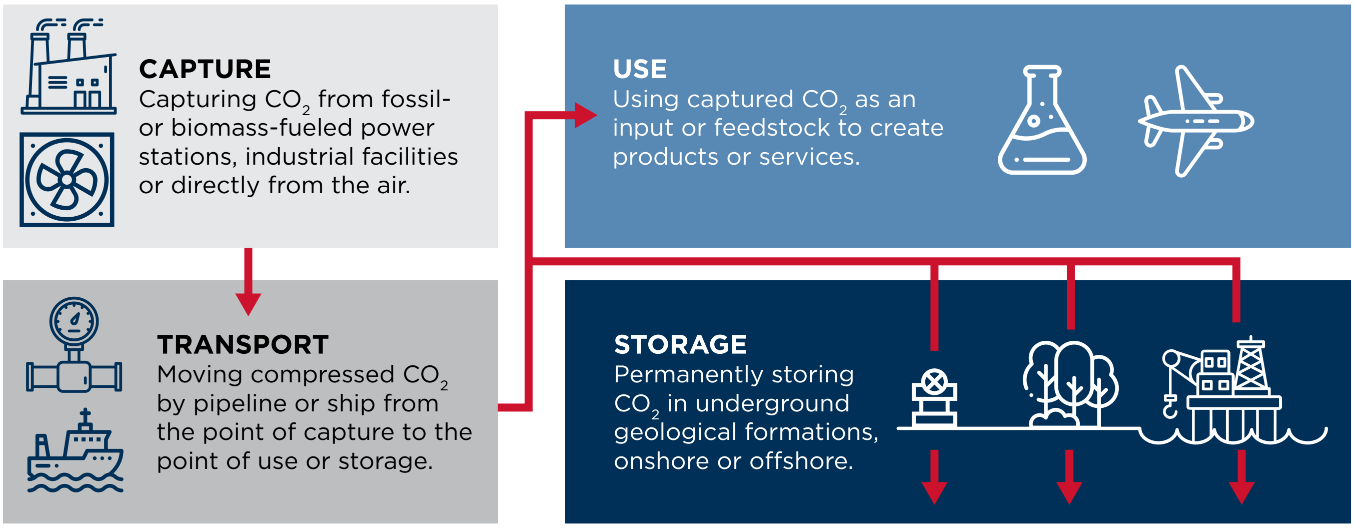

Figure 1 Illustration for CCUS shipping chain

According to the Global Status of CCS 2020 Report published by the Global CCS Institute, there are 65 commercial Carbon Capture and Storage facilities worldwide with 26 facilities currently in operation[3]; in total these facilities can capture and store approximately 40 Mt of CO_2 per year. Although the overall operational CO_2 capture capacity has steadily grown since 2010, the level of activity in carbon capture dwindled after 2011. However, along with the 2015 Paris Agreement, many governments established stronger climate policies and stakeholders exerted more pressures at private sectors for the ambitious GHG reduction targets, which increased the confidence of CCUS to play an integral role in achieving the targets. Since 2017, more than 30 new integrated facilities were announced. Consequently, the total global CO_2 capture capacity would increase to approximately 130 Mt per year, if all the projects announced are fully operational. Today, approximately 50 countries, states/provinces or cities and many more private companies announced their pledge to achieve net-zero emission by mid-century.

Many of the early facilities were developed to be a direct source capture from power generation or gas processing plants with CO_2 storage sites nearby. Recently, the concept of hub (Figure 2), an industrial center for CO_2, has gained popularity for its ability to sequestrate, dehydrate and liquefy CO_2 for transport from clusters of facilities. The hub model has already been proven successful in other industries like parcel movement and energy distribution. The hub system can greatly reduce the unit cost for transporting and storing CO_2 in the long term, though the capital cost for building infrastructure might increase difficulty when seeking financing. With CCUS hubs (i.e., collection hub, storage hub, etc.), it will be possible to add smaller industrial facilities to the network that would otherwise opt out due to practicality and cost.

[3] Excluding pilot and demonstration-scale CCS facilities

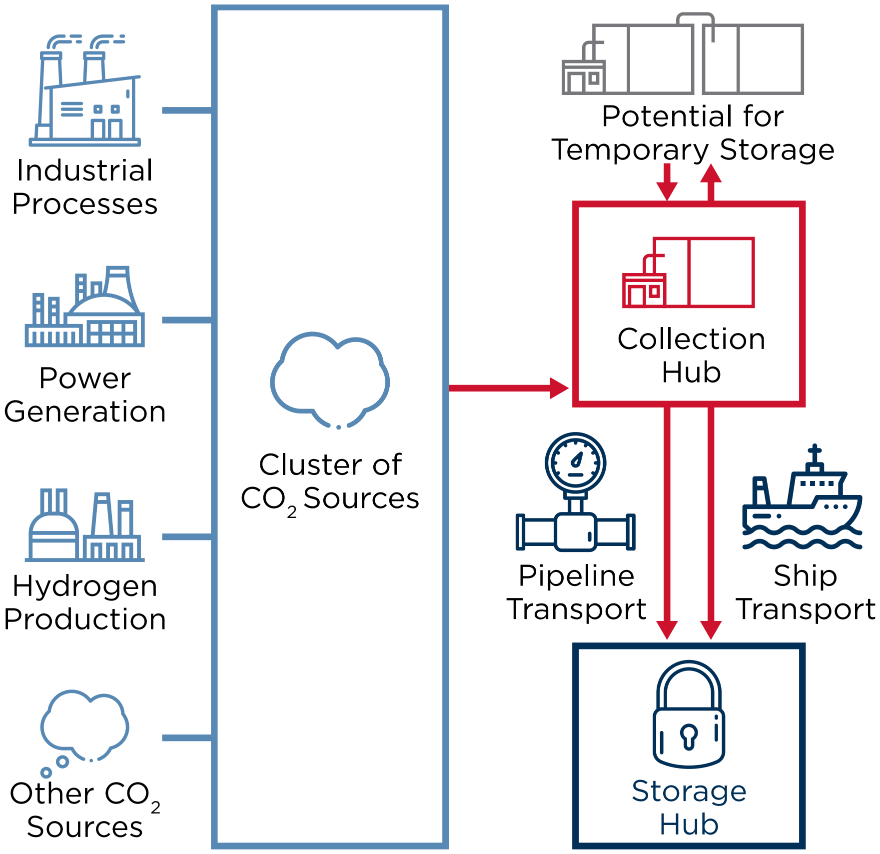

Figure 2 CCUS Hub Concept

Initially spurred by onshore carbon capture projects, the maritime industry sees a need for reliable and sustainable low-CO_2 shipping. In response to this new demand and increased interest in applications to both shipping and offshore oil and gas projects, research and development projects have been established in recent years to develop a better understanding of the economic and environmental feasibility of different approaches to partial and complete CCUS supply chains. There are still many technical and operational gaps, but these are being rapidly filled as the technology behind CCUS matures and its use becomes more widespread.

CARBON REDUCTION TECHNOLOGIES

Carbon capture consists of several technologies for removing CO_2 from pre-combusted hydrocarbon fuels or post-combustion flue gas. The technologies are practiced in power generation plants, heavy industrial sectors, such as cement and steel making, and chemical production, which collectively produce almost 20 percent of global CO_2 emissions. CO_2 can also be captured for fuel transformation at gas processing plants for ammonia, methanol and natural gas.

For some of these industrial sectors, due to production technology limitation, carbon emission is an unavoidable byproduct and can only be mitigated by carbon capture to reduce their emissions. For others, carbon capture is the most economical option to reach the emission targets. Implementing carbon capture technology or retrofitting to existing power plants become an economically practical method to reach net-zero emission targets.

Carbon can be separated with a variety of methods: membranes, solid sorbents, and liquid sorbents using a variety of solvents and have all been effectively used in onshore carbon capture projects.

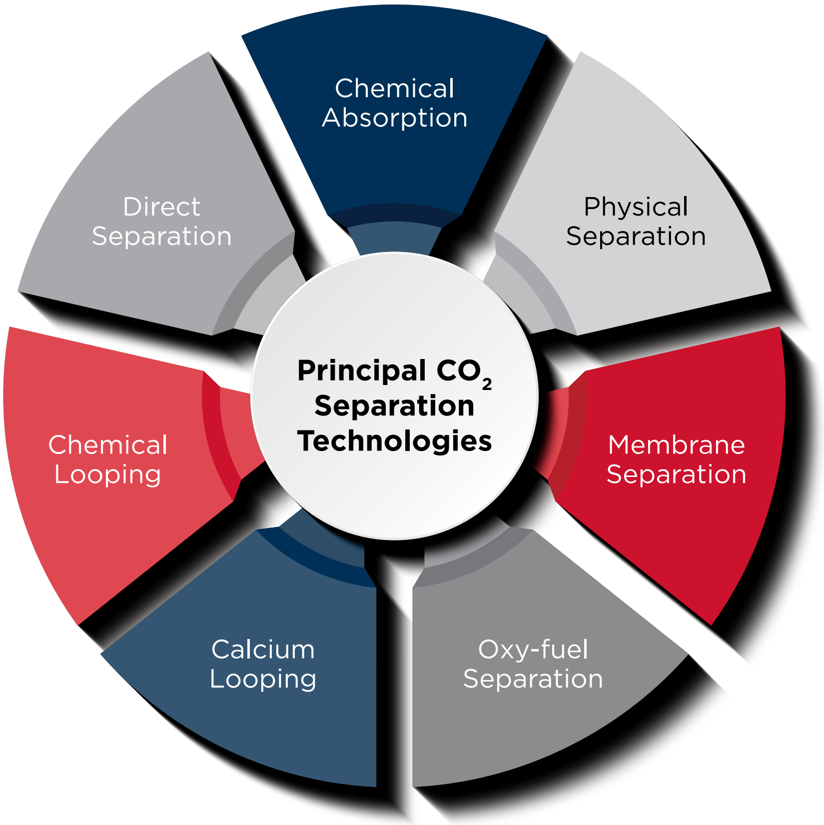

Figure 3 Principles of CO_2 *Separation Technologies*

When considering which carbon capture technology is most suitable for application, many factors such as the cost of installation, fuel and flue gas composition and properties, desired CO_2 concentration and existing facility compatibility should be taken into consideration.

The three major approaches to capturing carbon for industrial applications and power generation plants are:

1. Direct source carbon capture (from exhaust/flue gas or direct air)
2. Pre-combustion
3. Oxy-fuel combustion

Each method is discussed in the following section.

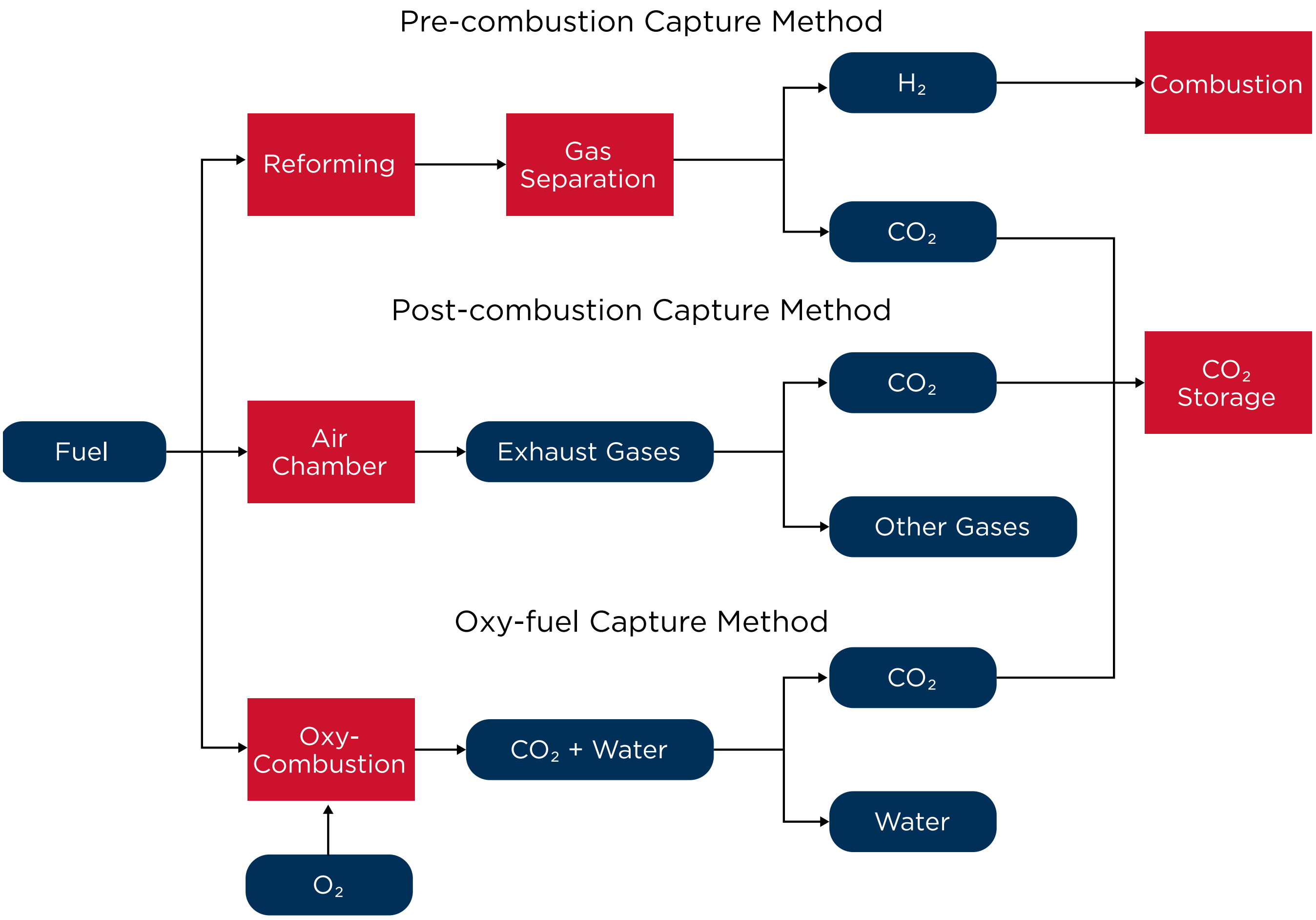

Figure 4 Three Carbon Capture Approaches

CARBON CAPTURE FROM EXHAUST GAS

POST-COMBUSTION

Post-combustion captures CO_2 in the flue gas after combusting a primary fuel such as coal, natural gas or heavy fuel oil. It has been commercially applied in many industries already, including coal-firing power plants and natural gas, combined-cycle plants. Membranes and absorption processes using a variety of solvents can be used to separate the CO_2 from the flue gas.

The CO_2 concentration from flue gas varies depending on the fuel used and can range from 3 percent to 14 percent by volume from power stations or industrial furnaces. Flue gas typically contains other components aside from CO_2 such as N_2 (nitrogen), O_2 (oxygen), H_2O (water), nitrogen oxides (NOx) and sulfur oxides (SOx), as well as traces of organic and inorganic particles. These can complicate the separation and purification process.

Post-combustion can be retrofitted relatively easily to existing plants without significant alteration to the existing infrastructure, but the CAPEX for engineering design and installation might still be significant. The CO_2 concentration in the flue gas might be lower than pre-combustion and requires more energy separating the CO_2.

SHIPBOARD APPLICATIONS

In response to the global effort of reducing GHG emissions, the International Maritime Organization (IMO) has pledged to reduce the CO_2 emissions from the global fleet (on a “per transport work” basis) by at least 40 percent by 2030 and 70 percent by 2050, and to reduce GHG emissions from shipping by at least 50 percent by 2050, compared to 2008. The maritime industry has explored many pathways to reaching the ambitious targets including the use of alternative fuels, energy saving devices, hybrid power system and aftertreatment solution such as an onboard carbon capture system. A post-combustion carbon capture system requires the least alteration to the existing ship designs and retrofitting options.

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Although current applications are mostly for onshore plants, the shipboard post-combustion application has been explored by many researchers and companies (Feenstra et al., Al Baroudi et al.) Most of the proposed concepts used amine-based solvents, such as monoethanolamine (MEA), with varying concentrations. A study by Jian et al. evaluated the use of aqueous ammonia for the combined removal of SOx and CO_2 on a ship using heavy fuel oil.

A recent concept study focused on installing a marine carbon capture and storage unit on a very large crude carrier. The system was comprised of four towers for cooling the exhaust, absorbing CO_2, treating the exhaust and regenerating the CO_2, in addition to the required liquefaction and storage facilities. The objective of the study was to investigate onboard production of methane or methanol by combining hydrogen from water electrolysis with the captured CO_2. The study reported CO_2 capture rate at about 86 percent, and a 20-year return due to the high CAPEX and OPEX.

The cost of capture varies depending on the capture technology being used, the power rating of onboard combustion units and the fuel being used. It is possible that this cost could be offset through the sale of the captured carbon dioxide for use in other industries. Regardless, additional research is still needed to determine the economic and environmental feasibility of onboard carbon capture for vessels.

DIRECT AIR CAPTURE

Direct air capture (DAC) extracts CO_2 directly from the atmosphere. This is a new option researchers are looking to use to offset the residual emissions from sectors or places that are difficult to accommodate otherwise. The DAC can be located in any desired location for ease of use; however, the significant impediment for DAC is the low CO_2 concentration in ambient atmosphere comparing to direct source capture. The low concentration translates to high energy consumption and thus high cost.

There are three major sorbents for DAC: 1) a liquid sorbent with hydroxide solution (L-DAC) 2) solid sorbents with a CO_2 filter (S-DAC); and 3) amine-based chemical sorbent. S-DAC can be operated solely on electricity and requires relatively low operating temperature (approx. 100°C), which can potentially be renewably sourced, but L-DAC needs higher operating temperature (approx. 900°C) that likely requires combustion from fuel such as natural gas

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Currently there are 15 DAC plants operating in Canada, Europe and United States. While most are small-scale pilot and demonstration plants, the commercial plants sell the captured CO_2 to greenhouses and for beverage carbonation.

COMBUSTION TECHNOLOGIES

OXY-FUEL COMBUSTION

Oxy-fuel combustion combusts fuel with pure oxygen rather than air, which contains nitrogen, to produce a flue gas consisting mostly of CO_2 and H_2O for improved ease of sequestration. The flue gas from oxy-fuel combustion is cooled to remove condensed H_2O vapor and usually left with 80-98 percent CO_2. However, due to power consumption increasing drastically when trying to obtain higher CO_2 concentration, most operations will adopt 95 percent concentration. Compared to post-combustion, oxy-fuel combustion can cost more for the additional oxygen input required.

With pure oxygen, the combustion temperature can reach about 3,500°C, which is much higher than for a typical power plant design and can potentially cause damage to furnaces; therefore, the high purity O_2 might be diluted by the recycled flue gases to decrease the flame temperature. Recirculating wet recycled flue gas to the combustion chamber can avoid significant energy loss. However, due to the acid nature, it can cause corrosion and erosion damages. Therefore, dry flue gas is recommended for diluting the oxygen stream.

PRE-COMBUSTION

Pre-combustion separates the CO_2 from the primary fuel in a reactor prior to combustion, leaving mainly H_2 for use. The primary fuel is usually put through a reactor to generate a synthesis gas (syngas), which means a fuel gas mixture consisting of primarily H_2, CO and CO_2.

There are two ways to create syngas from primary fuel by adding: 1) steam for "steam reforming"; or 2) oxygen for partial oxidation.

Steam Reforming
$C_xH_y + xH_2O \leftrightarrow xCO + (x+y/2)H_2 \quad \Delta H + ve$
Partial Oxidation
$C_xH_y + x2O_2 \leftrightarrow xCO + (y/2)H_2 \quad \Delta H - ve$
Water Gas Shift Reaction
$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \Delta H\ -41\ kJ\ mol^{-1}$

Then the syngas will undergo the water-gas shift reaction to convert CO and water to H_2 and CO_2, and the CO_2 can be sequestrated for storage. The CO_2 concentration can range from 15-60 percent after removing moisture.

Hydrogen is a low- to zero-carbon fuel that is often seen as a feasible solution to meet the GHG reduction targets for the mid-century. It is commonly produced by steam methane reforming while using CCUS and is referred to as "blue hydrogen". Hydrogen can be produced through electrolysis powered by renewable-based electricity to achieve net-zero emissions ("green hydrogen"), but currently the CCUS-equipped hydrogen production from natural gas or coal is still more economical. Certainly, the cost of electrolysis will decline over time, but CCUS-equipped blue hydrogen production is likely to remain a competitive option for some time. More details on hydrogen as a marine fuel are available from ABS.

CARBON STORAGE AND TRANSPORTATION

Compared to shipboard-based CCUS, the transport of onshore-generated carbon has a much longer history. The most efficient mature transportation method for CO_2 is via pipeline, which has its own unique challenges and factors. As with traditional transport methods for the petrochemical industry, it is likely that a hybrid pipeline-ship system would emerge for CO_2 with pipelines connected to terminals for loading and offloading from ships. The transportation of onshore-captured CO_2, and the offloading of ship-captured carbon dioxide both require significant infrastructure investments in ports. There are many aspects to consider for storing and transporting captured CO_2.

CO_2 CONDITIONING

PURIFICATION

The captured CO_2 stream needs to be purified and then conditioned in a dehydration and liquefaction system before transporting in pipelines and tanks. This step is analogous to natural gas and hydrogen liquefaction that also occurs before loading onto a carrier or into a tank for storage.

Table 1 Examples of possible components in the captured CO_2 stream before compression from post-combustion

Possible Components in CO_2 Stream
CO_2
H_2O
Ar
N_2
O_2
SO_2

The captured CO_2 stream, depending on the approaches used, might contain traces of various components such as H_2O, O_2, hydrogen sulfide (H_2S), H_2 (hydrogen), and SO_2 that negatively impact the storage and transportation conditions. The presence of soluble impurities can also have major impact on the CO_2 density, which can affect the design parameter and operational profile of the piping and storage systems.

The CO_2 stream will likely go through purification, but the extent of purification varies depending on the geographical locations and final use of the CO_2 stream.

The impurities in the CO_2 stream can cause serious damage to the pipeline. Water, O_2 and sulfur-containing substances such as SOx or H_2S can lead to localized corrosion and pitting. These impurities can cause pressure drop in the CO_2 stream and result in two-phase flow that liquid sludge in the pipeline, liquids and/or solids (dry ice) in the injection compressors. Moreover, the impurities under a high pressure environment can form new products with the CO_2 stream that can be toxic and harmful to surroundings.

For utilization or permanent storage applications such as EOR, a very low oxygen content is allowed due to the highly flammable properties of O_2. Oxygen reacting with hydrocarbons can cause overheating at the injection point or oxidation in the reservoir with higher oil viscosity and increasing operational costs. The presence of oxygen can also increase unwanted biological growth near the production site.

DEHYDRATION

Water in the CO_2 stream is common but unwanted. Therefore, dehydration is important for the CO_2 stream before entering pipeline or storage.

While there is currently no uniform consensus on a minimum acceptable level of moisture, a maximum allowable water content is generally regarded between 10-50 ppmv[4], or less than 60 percent of the dew point to avoid operational issues such as corrosion, freeze, and hydrate formation when operating with liquified CO_2.

There are many dehydration techniques that can be applied to the CO_2 stream. Some techniques might not offer enough dehydration but can help to offload the main dehydration unit. A main dehydration unit, for example, can make use of liquid desiccants such as Triethylene glycol (TEG). Further dehydration techniques that can be applied to CO_2 stream are mentioned in Kemper et al.

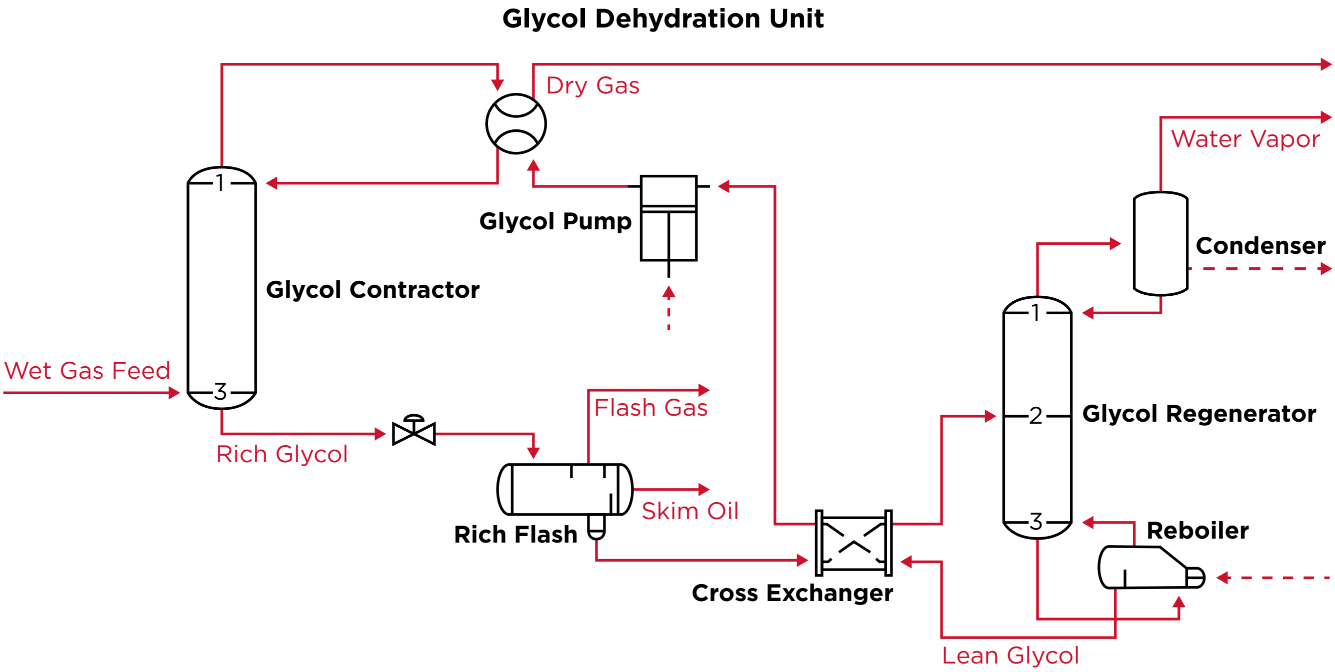

Figure 5 Schematic of a Basic TEG Dehydration Unit

LIQUEFACTION

Liquefaction is an important aspect of CCUS that also consumes a lot of energy. Aspelund et al. suggested that liquefaction alone takes 77 percent of the energetic requirement of the transmission chain, Lee et al. suggested liquefaction takes up to 10 percent of the total consumption for the entire CCUS chain.

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[4] Parts per million volume

CO_2 can be liquified at various pressures between the triple point (0.518 MPa, −56.6°C) and critical point (7.38 MPa, 31.1°C). The liquefied CO_2 at such temperature and pressure, can take approximately 1/500th of the volume of CO_2 in gaseous form at standard temperature and pressure. When pressured above its critical temperature and critical pressure (8 Mpa), the CO_2 can be compressed to reach supercritical form that has a higher density and can avoid two-phase flow.

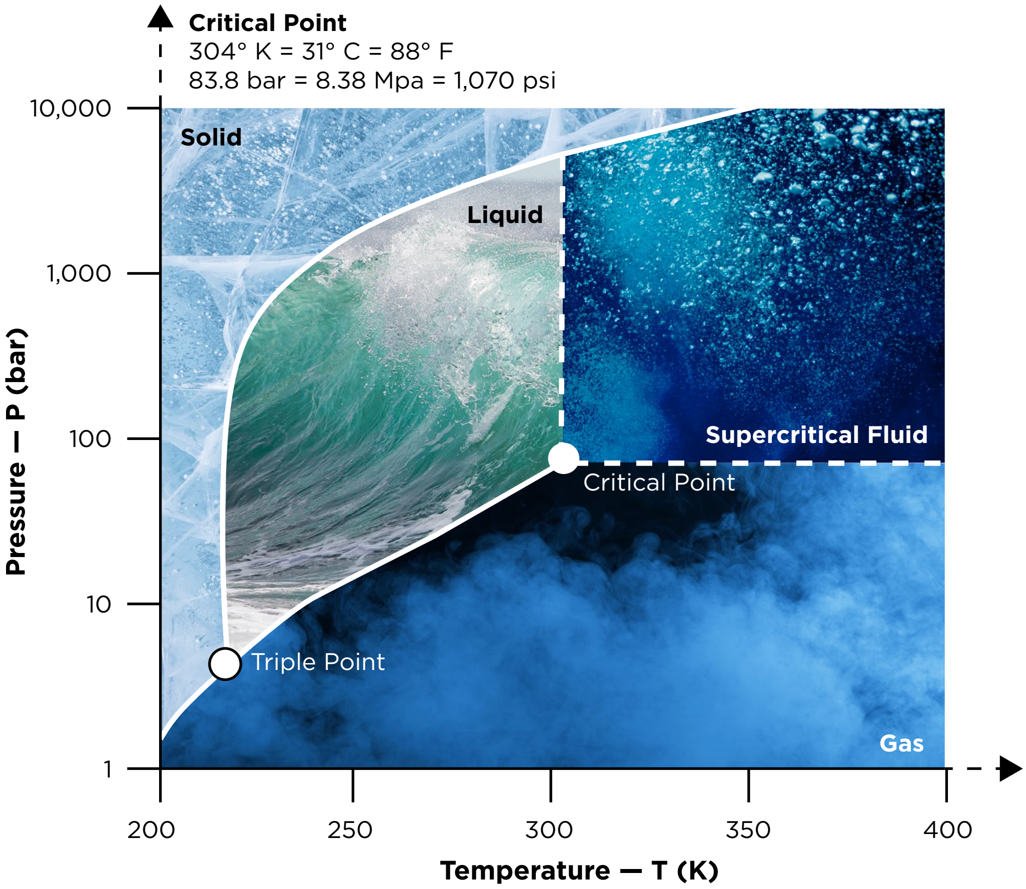

Figure 6 CO_2 Pressure-temperature (phase) diagram

The two major types of liquefaction systems are open cycle and closed cycle. In an open cycle, or internal refrigeration system, the CO_2 stream is compressed to higher than intended condition prior expanding to a single or multi-stage expansion. In a closed cycle or external refrigeration system, the CO_2 stream is compressed to the desirable liquefaction state with external coolants.

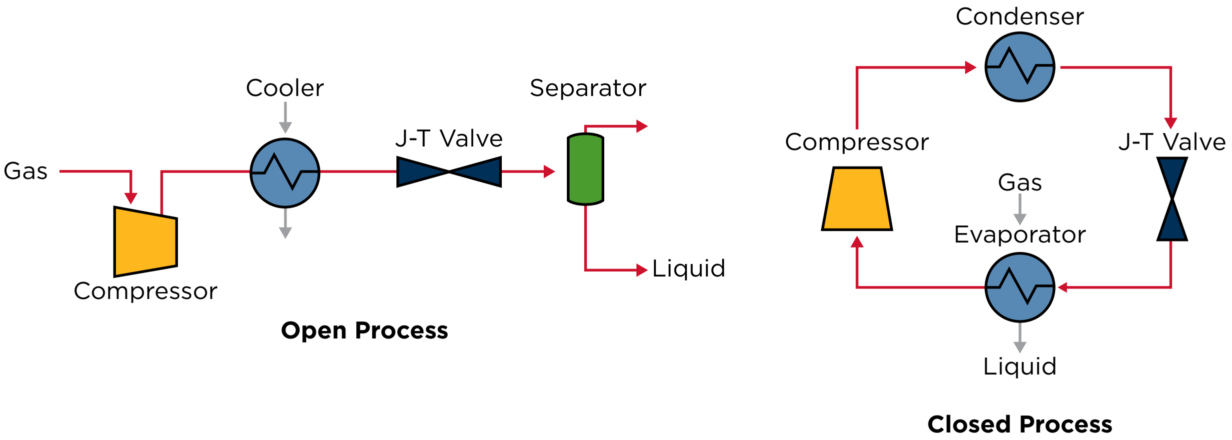

Figure 7 Open cycle and close cycle for liquefaction

Many studies have been conducted to determine the optimal liquefaction pressure. Most literature recommends conditions near the triple point for shipping of liquefied CO_2, for the benefit of lower storage costs and enhanced density. However, other research suggests a higher liquefaction pressure at 6 MPa and 21.85°C (295 K), for higher energy efficiency. Thus, there is no set optimal liquefaction pressure for all conditions; it should instead be determined from individual needs and the wider chain and project variables.

CO_2 TRANSPORTATION

There are several different methods already being used for the transportation of CO_2. Table 2 provides an indication of the amount carried; unsurprisingly, the pipeline and marine shipping sectors have the most capacity.

Table 2 CO_2 Transportation capacity comparison (Al Baroudi et al.)

Transportation Methods	Capacity	CO_2 Phase
Pipeline	~100 Mt CO_2/year 6500 km of Pipeline Transport in Operation	Dense Vapor
Ship	>70 Mt CO_2/year	Liquid
Motor Carrier	>1 Mt CO_2/year	Liquid
Railway	>3 Mt CO_2/year	Liquid

ONSHORE TRANSPORTATION

Pipeline transportation is well suited for the movement of large volumes of CO_2 over long distances between fixed locations. CO_2 pipelines have been in use for over 50 years in the oil and gas industry where they provide injection media for enhanced recovery. Pipelines are designed and constructed for the required temperature and pressure characteristics and using necessary materials to avoid corrosion, pitting, or cracking when considering the content of the CO_2 stream (e.g., accompanying water, nitrogen, hydrocarbons, oxygen, sulfur and sulfides). Attention also needs to be paid to the materials used in pump seals and other machinery expected to come in contact with the CO_2 stream.

Routing of pipelines has thus far avoided large population centers but extensive pipeline networks for large scale CCUS transport may be more of a challenge. It will be important to minimize risks associated with potential releases since CO_2 is colorless and odorless but is a hazard to people when released and will accumulate in enclosed spaces or depressions. Risk management should include such aspects as inspection, maintenance, leak detection, and other means to reduce the likelihood of a release and to minimize its extent in case a release does occur.

Permanent storage of CO_2 underground will require thousands more miles of pipeline, both as main trunk lines and feeders from industrial sites where it is captured. Existing pipelines are unlikely to be suitable for repurposing in many cases due to the differences in design parameters.

For offshore storage, the CCUS industry will build on similarities to typical infrastructure for oil and gas distribution. Terminal facilities will be needed for transition from land to subsea pipelines or to ships. Subsea pipeline and termination manifolds as well as riser connection to fixed or floating offshore platforms are also well understood. Transfers from ship-to-ship or from ship to floating platform will require analysis of relative motion parameters in the design of the transfer system, in a similar manner to recent developments in LNG ship-to-ship transfer developments.

The installation of new pipelines is capital intensive, especially offshore. Operating expenses for monitoring and inspection/maintenance are also a factor in the overall project evaluations especially with the potential technical challenges with materials in contact with the CO_2 stream.

TRANSPORT OVERVIEW

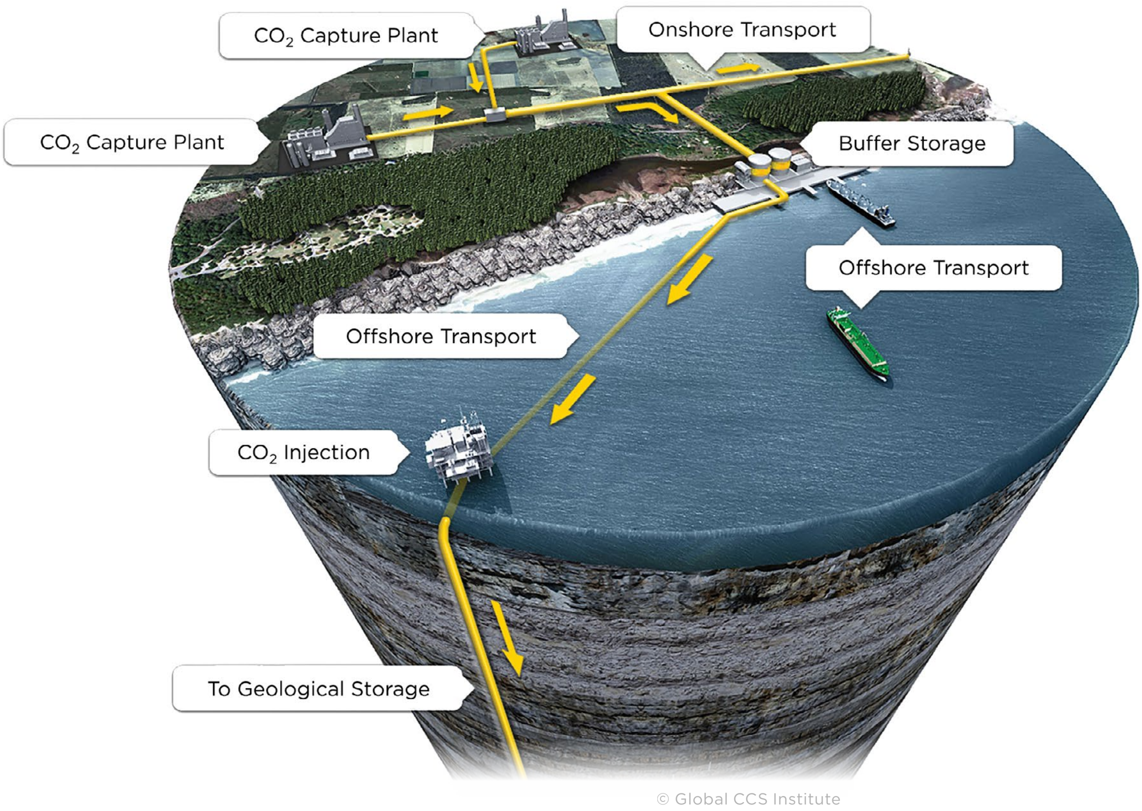

Figure 8 CO_2 Transport Overview

MARINE TRANSPORTATION

While the infrastructure supporting liquefied CO_2 shipping is being explored, the fleets carrying liquefied CO_2 are also being examined by the industry. The design concepts for CO_2 carriers are varied in nature, depending on the storage pressure requirements during transit. Important elements that are expected to impact the design of the ships include as CO_2 purity, loading and offloading pressures/temperatures at the onloading and offloading locations, and the impact of pressures/temperatures on tank design and on loading/offloading. Types of tanks suitable for the transport of liquid gases include: 1) pressure tanks manufactured to limit boiling of their contents at ambient temperatures; 2) low-temperature tanks suitable for large-scale transport and designed to operate at low temperatures; and 3) semi-refrigerated tanks that are both pressurized and cooled.

For CO_2 specifically, only semi-refrigerated type C tanks are likely to be feasible for larger capacity transport ships. At low pressures, the design would be similar to that of an LPG vessel, with large cylindrical tanks. At medium pressures, transport would be possible using vessels typically used in the commercial food and brewing industry. At high pressures, the liquefied CO_2 would need to be transported in much smaller vessels, requiring hundreds of individual tanks. In the food and brewing industry, CO_2 is shipped at 1.4-1.7MPa and -35 to -30°C but only in smaller vessels suitable for roads. The same issue is also found in current liquefied CO_2 marine transport, where only small amounts are transported at lower pressures.

For example, existing CO_2 carrier has a capacity approximately 1,000 tons of CO_2. For vessels that need to carry more CO_2, there will likely be substantial design changes The challenges to be addressed in the coming years will deal more with upscaling and optimizing designs of larger vessels for efficiency. In March 2021, ABS signed a joint development project with Marshall Island Registry, Hyundai Mipo Dockyard, and its parent Korea Shipbuilding & Offshore Engineering to develop a new design for a liquefied CO_2 carrier.

UTILIZATION

REUSE OPTIONS

CO_2 is a key input in many industries. The current demand for CO_2 is around 230 Mt globally per year, and the fertilizer industry alone consumes 125 Mt per year as a raw material in urea manufacturing. Oil and gas producers use around 70-80 Mt per year for EOR. CO_2 is also an integral part of food and beverage production, cooling, water treatment and agriculture, but the demand is relatively small. The processing of the CO_2 stream differs since CO_2 suitable for EOR or some other industrial uses will not likely be suitable for food and beverage production, and carriage requirements are impacted by purity. Other opportunities for utilizing CO_2 and fuel production for methane and methanol are envisioned as an energy chain for the future.

CO_2 ENERGY CHAIN FOR LNG

One innovative adjustment to the CCUS supply chain would include the shipping of LNG produced at offshore assets to a shore-based power plant for power generation. Then, liquified inert nitrogen (LIN) and liquified CO_2 produced by the power plant are transported back to offshore assets to produce more LNG before gasification, heating, and injection back into the well as an enhanced oil recovery method. This process, proposed by Aspelund and Gunderson, is predicted to yield an energy efficiency of up to 87 percent and 71 percent respectively, for the offshore and onshore processes. A process like this would also be incredibly carbon efficient, as the majority of the produced CO_2 from the oil field would be returned to the field later. This proposed process would require extensive port infrastructure investments, a novel ship design that would be capable of transporting LNG, LIN, and CO_2,and an additional system on the offshore asset to support gasification and injection back into the oil field.

CO_2 ENERGY CHAIN FOR METHANOL

The CO_2-produced methanol energy chain concept was first proposed by Olah et al. in the book entitled Beyond Oil and Gas: The Methanol Economy as an alternative to hydrogen. Methanol, or methyl alcohol, is a well-known chemical that has been used by many industries for decades. It is colorless liquid under normal conditions and can be managed relatively easier than other low- or zero carbon fuels, which often need to be cryogenically liquified. Methanol is commonly produced from natural gas and can be manufactured by hydrogenation of CO_2.

$$CO_2(g) + H_2(g) \leftrightarrow CH_3OH(g) + H_2O(g)$$

Today, CO_2-produced methanol is being studied by many companies. Many pilot projects are studying the feasibility for producing methanol with recycled CO_2 emission and waste plastics, etc. to eliminate the overall carbon footprint.

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PERMANENT STORAGE

There are a few permanent storage options to consider for CO_2. One of the most common solutions is offloading it to offshore oil and gas wellheads, where it would be used as a method of EOR while simultaneously being permanently stored. Direct injection from the ship to the wellhead is possible, but still unproven. It is more likely that the CO_2 would be offloaded to a buoy and flexible riser. In both cases, the ship would require conditioning, pressurization, and heating systems before pumping into the well could proceed.

The overall estimated storage potential for CO_2 in offshore oil and gas fields is vast but not precise. Though from the production rates of oil and gas, it is clear that the global geological storage capacity for CO_2 is enough to accommodate the net-zero emissions under any scenarios.

INJECTION TO WELLS

Long-term storage of CO_2 is accomplished by injection into natural porous rock formations such as depleted oil or gas reservoirs, coal beds, or saline aquifers.

For many years, CO_2 has been injected during hydrocarbon production as an enhanced oil recovery (EOR) method to stimulate additional returns from the well; similar application of CO_2 is in enhanced coal bed methane (ECBM) recovery. For the long term, CO_2 may be stored deep underground as a goal in itself rather than an associated production process. There is potential for storage in many depleted reservoirs or unmineable coal beds globally, provided that the formation conditions are satisfactory for such use. Deep saline aquifers are also potential locations for long term CO_2 storage.

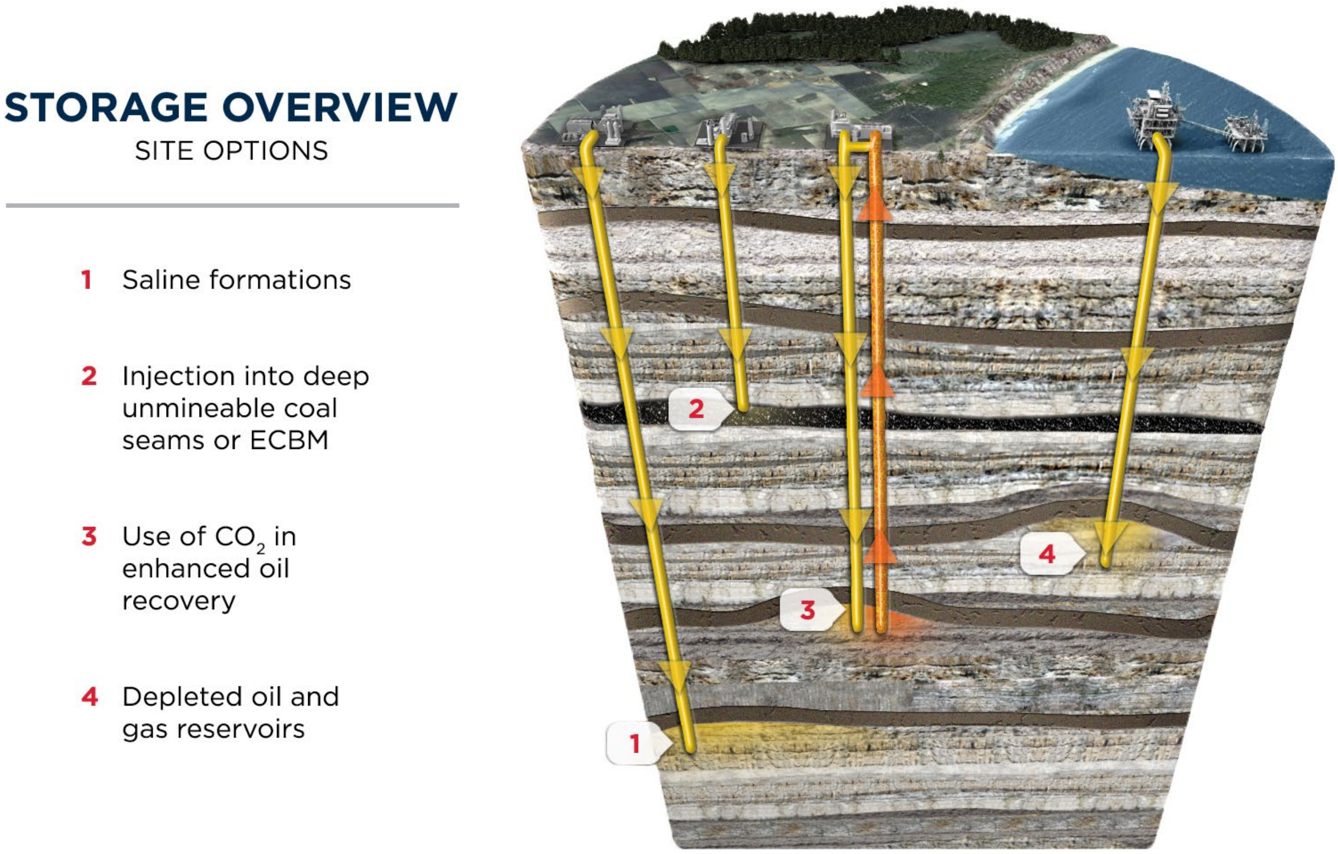

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Figure 9 CO_2 Storage Overview for Site Options

Geological sequestration of CO_2 is performed with the substance as a supercritical fluid, i.e., above its critical temperature and pressure on the phase diagram.

It is important to evaluate a proposed location to identify that the storage capacity is adequate for the volume to be placed, the formations can absorb CO_2 at the desired rate of injection, and that in the long term, the stored material remains underground and does not migrate into other areas of soil, groundwater or the atmosphere. Migration can occur either naturally or through abandoned wells or via faults and fractures. Depth (i.e., pressure), salinity, temperature, and the porosity and permeability of the storage reservoir rock are some key parameters along with the geophysical features such as faults.

There are several mechanisms that act to retain injected CO_2. The CO_2 is trapped in a formation due to physical barriers to migration, such as domes, faults, or stratigraphic differences in rock type and permeability. It will also be trapped locally among voids in the rock material, analogous to a sponge retaining water. In the long term, stored CO_2 may interact chemically with minerals to form a solid; it may also dissolve into salty water in the formation and settle downward. Overall, it has been estimated that over 98 percent of the injected CO_2 will be permanently sequestered and unable to escape the downhole location.

For injection activities offshore, existing oil and gas platforms and facilities (both fixed and floating) can be involved in the injection of CO_2 for EOR or for storage. In the latter case, consideration needs to be made for powering and operating the facility from the OPEX standpoint as well as CAPEX for additional or new equipment and potentially life extension of the structure and its mooring (if floating) and injection risers. This will be in addition to the expenses incurred in plugging and abandoning the depleted wells. It may not be possible to reuse infrastructure if it was not designed and constructed with CO_2 injection service in mind due to differences in fluid pressure, temperature and necessary material properties as previously mentioned with respect to potential corrosion, pitting, or cracking.

OFFSHORE PLATFORMS

A wide range of offshore platform types could be used in the injection of CO_2 to storage below the seabed. Depending on CO_2 throughput and the water depth, it may be possible to re-use fixed platforms or floating facilities since they are already located close to the potential storage reservoirs. Due to the available lifespan, life extension of the structures may be necessary.

Deck space and power generation are needed for machinery used to process the CO_2 into a supercritical fluid for injection, but there is typically ample available space and power on a fixed platform, spar, tension leg platform, or semisubmersible. Operating cost for large platforms previously used for oil and gas extraction may be high, however, and this would drive new construction of smaller, purpose-built offshore CO_2 facilities with multiple injection well centers. In particular, ship-type production units like FPSOs would not be well suited for injection platforms since their large oil storage capacity is not useful with CO_2 and the inspection and maintenance costs associated with the large hull structures would be high.

In order to avoid leaks, existing wells must be properly plugged and abandoned. Injection wells will need to be drilled and completed; previous production wells do not have casing and tubing designed for CO_2 injection pressures, temperatures, and chemical properties. Proper well design and availability of drilling rigs will be factors in the same manner as oil and gas production. Consideration should also be given to other operations that may be needed such as workover or new wells during the life of the injection platform, and interventions to deal with sand, water, or pressure issues downhole which may arise and impede continued injection.

Offshore facilities have the potential for reduced manning or remote control and /or autonomous operation to reduce operating cost and consolidated management. More details on reduced manning are available from ABS.

MINERAL CARBONATION

Another option for CO_2 permanent storage is in mineral carbonation. By allowing gaseous CO_2 to react with alkaline mineral resources, the CO_2 binds to a solid carbonate form that can then be securely stored. Resourcing alkaline feedstock from industrial waste is also being considered, which would be mutually beneficial if applicable. In an in-situ scenario, CO_2 can be injected directly into geologic formations with high concentrations of divalent cations such as basaltic rocks. A pilot project in Iceland near a geothermal power plant has been investigating this topic for more than a decade. This experiment has shown 95 percent of CO_2 and all the H_2S injected have been carbonated within the first year and the first four months, respectively. This allows the power plant to reduce CO_2 and H_2S emission by 34 percent and 68 percent respectively.

REGULATORY ASPECTS

INTERNATIONAL MARITIME ORGANIZATION (IMO)

The IMO aims to reduce the CO_2 emissions from the global fleet and has set targets to reduce at least 40 percent by 2030 and 70 percent by 2050. The IMO also intends to reduce GHG emissions from shipping by at least 50 percent by 2050, compared to 2008. The current regulatory framework mainly focuses on energy efficiency applications and utilization of alternative fuels. Carbon capture has not been included for the current agenda.

However, the IMO recognizes the potential for carbon capture and sequestration in sub-sea geological formations (CCS-SSGF) in the London Protocol and London Convention (LP/LC). In 2016, the CCS-SSGF was adopted to the LP as amendments to Annex I that provides an international legal basis for regulating carbon capture and storage in sub-seabed geological formation for permanent isolation. The amendments applied to carbon capture mainly from industrial plants with direct source of CO_2 emission, and excludes the use for EOR.

The LP Contracting Parties later amended Article 6 to include the export of wastes for dumping purposes in 2009. This amendment ensures the sharing of transboundary sub-seabed geological formations for sequestration projects given that the protection standards of LP are fully met.

The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) is the relevant instrument defining marine vessel design safety requirements for carriage of liquefied CO_2 by ship.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

Carbon capture has been applied to land-based facilities such as coal-fired power plant for decades; however, there has been a lack of widely recognized standards for carbon capture. The first internationally recognized standard, CSA Z741 -12 Geological storage of carbon dioxide, was jointly developed and adopted by the Standards Council of Canada (SCC) from Canada and American National Standards Institute (ANSI) from the U.S. in 2012. This standard was the first formally recognized CCUS standard for commercial deployment.

Following the success from Z741, ISO established the technical committee, TC 265 Carbon dioxide capture, transportation and geological storage committee, in 2012. The objective of the committee is to develop and standardize a set of rules to effectively be applied to CCUS projects. The committee currently consists of 19 participating members and 13 observing members worldwide.

As of today, the ISO/TC 265 has published 10 ISO standards with five under development. These documents include review and recommendations for design, construction, operation, environmental planning and management, risk management, quantification, monitoring and verification, and related activities in the field of CCUS.

DOMESTIC REGULATIONS

In large, industrialized economies, much of the regulatory framework will be domestic since transported CO_2 maybe used domestically and thus would not cross a border or be carried on a "Convention voyage" between countries; indeed, cabotage may be a factor in many jurisdictions and could limit the applicability of international regulation. It is to be expected, however, that the technical requirements are similar and based on international work in standards development (such as ISO) and will mirror internationally agreed requirements (as at IMO). Management systems and reporting may differ.

As examples, refer to the EU Carbon Capture and Storage Directive (CCS Directive) 2009/31/EC; the U.S. Environmental Protection Agency (EPA) Greenhouse Gas Reporting Program in 40 Code of Federal Regulations (CFR) subparts PP, UU and RR; and the China CCUS policy system including specialized and unspecialized (i.e., common to other purposes) rules and regulations as part of the roadmap of the Five Year Plan. While each country may incorporate standards by reference, the final jurisdiction is with the local authorities.

ABS SUPPORT

ABS has experience in fracture mechanics and stress corrosion cracking which are necessary for CCUS analyses. ABS is also equipped to assist owners, operators, shipbuilders, designers, and original equipment manufacturers as they consider practical implications and risk assessments of CCUS. Services offered include:

- Marine vessel design and construction support for classing CO_2 carriers and offshore facilities
- Techno-economic analyses
- Certification based on public ISO standards
- Certification of subsea pipelines
- Risk Assessments
- Pipeline materials study to assess the suitability of offshore pipelines for reuse in CO_2 transport
- Novel Technology Qualification
- Qualifying new carbon capture technology
- Qualifying new uses for existing infrastructure
- Qualifying new infrastructure
- Hazard Review

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LIST OF ACRONYMS AND ABBREVIATIONS

ABS	American Bureau of Shipping
ANSI	American National Standards Institute
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CCS-SSGF	Carbon Capture and Sequestration in Sub Sea Geological Formations
CCUS	Carbon Capture, Utilization and Storage
CDR	Carbon Dioxide Removal
CFR	Code of Federal Regulations
CO_2	Carbon Dioxide
DAC	Direct Air Capture
ECBM	Enhanced Coal Bed Methane
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
EU	European Union
GHG	Greenhouse Gas
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen Sulfide
IEA	International Energy Agency
IMO	International Maritime Organization
IOGP	International Association of Oil &Gas Producers
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LIN	Liquified Inert Nitrogen
LNG	Liquefied Natural Gas
LP/LC	London Protocol and London Convention
LPG	Liquefied Petroleum Gas
MEA	Monoethanolamine
Mt	Megatonnes
N_2	Nitrogen
O_2	Oxygen
OPEX	Operational Expenditures
SCC	Standards Council of Canada
SOx	Sulfur Oxides
TEG	Triethylene Glycol
UN	United Nation
UNFCCC	United Nations Framework Convention on Climate Change
NOx	Nitrogen Oxides

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