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CARBON DIOXIDE (CO_2) CAPTURE TECHNOLOGIES AND COST

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Abstract

This paper explores the advances in carbon capture technologies and their related costs. Our efforts are to cut down net greenhouse gas (GHG) emissions to zero by implementing carbon dioxide (CO_2) removal strategies. Various CO_2 removal technologies and their related costs have been discussed in this paper. Despite significant global efforts, the CO_2 concentration in the air continues to rise, underscoring the need to deploy all available emissions reduction technologies. CCS plays a crucial role in achieving net zero targets as per the mutually agreeable Paris agreement clause, permitting CO_2 capture from hard- to-abate industries such as cement, steel, and chemicals, alongside the decarbonisation of power generation. With the growth of CCS industries, scientific advancements and economies of scale have started to reduce the costs of capturing and storing CO_2. This write up carries out an in-depth analysis of capture technologies and the CCS cost structures, the factors influencing cost variations, and strategies for cost reduction. The capture segment, which typically represents the largest portion of overall CCS costs, has shown tremendous improvements in both established and emerging sectors. This paper outlines the common and novel CO_2 capture processes deployed commercially and the ones under development. The methods given are assessed for their applicability, maturity, and cost-effectiveness in different industrial contexts. The CCS is deployed in over 620 projects world over, with more than 50 operational facilities, CCS deployment continues to grow globally. The costs involved in a typical CO_2 capture plant, as well as the major cost drivers and strategies for reducing these costs have been examined here. The overall trend in costs are also expanded upon with further studies and deployments across sectors enabling a deeper understanding of how costs changes with new facilities. To achieve net zero targets CCS technology needs to be adapted globally. CCS can directly reduce emissions across most industry sectors in both retrofit and new build applications. In hard to abate industries where CO_2 generation is unavoidable, such as cement manufacture, ethanol fermentation, and ethylene oxide production, CCS is the only method to address CO_2 emissions and enable these facilities to achieve their targets.

Keywords: CCS-Carbon Capture and Storage/Sequestration, CO_2- Carbon Dioxide, GHC-Greenhouse Gas Emissions, CDR-Carbon Dioxide Removal, BECCS- Bioenergy with CCS, TRL-Technology Readiness Level, DCC-Direct Contact Coolers, MEA-Mono Ethanol Amine.

Introduction

To address the impacts of climate change, net greenhouse gas emissions must fall to zero, and greenhouse gases must be actively removed to address the unchecked emissions. As per the Mauna Loa, Observatory in Hawaii (NOAA, 2024) the common greenhouse gas in the atmosphere, carbon dioxide or CO_2, continues to climb, with the monthly mean concentration surpassing 426 ppm. This observed increasing trend, highlights that humanity is rapidly approaching the limit of Earth's carbon budget before violating the mutually agreeable Paris Agreement. The technologies that underpin CCS continue to evolve. In several sectors, extraction of CO_2 from process streams has been conducted for decades, and the technology is well-established and mature. In other sectors, CCS is a novel opportunity, ripe with the potential to develop and improve to bring the cost associated with CO_2 emissions down. In all cases, wider development, deployment, and experience gathering are driving down the costs to capture, transport and store CO_2. A sound understanding of the current technology status for carbon capture and key factors that impacts costs and a breakdown of the subcomponents of cost in each facility, enables clearer and more impactful decision-making for accelerating the deployment of CCS globally.

Overview of CCS- CCS is a well-established and benign knowhow that can either prevent CO_2 from being discharged from a point source into the atmosphere (Point Source Capture) or take it away directly from the atmosphere (Carbon Dioxide Removal or CDR). CCS is generally divided into three main sections; Capture, Transport, and Storage/Sequestration. CO_2 Capture refers to the process in which CO_2 is detached from a specific gas stream and changed into a purified stream of CO_2. Point Source Capture comprises of the capture of CO_2 from distinct, discrete sources within an industrial plant such as cement plant, chemical plant, steel mill, or power plant. These distinct sources have above average concentration of CO_2 in comparison to overall atmospheric CO_2 levels, from 50 mole% in hydrogen tail gas to about 3% in natural gas combined cycle (NGCC) flue gas. Carbon Dioxide removal entails the capture of CO_2 from the environment, including air with a CO_2 concentration of 426 ppm or 0.0426%. The CO_2 removal comprises of Direct Air Capture(DAC), Direct Ocean Capture, and Bioenergy with CCS (BECCS). The CO_2 separated from a capture plants will be of higher CO_2 purity, often above 95%. This CO_2 is dried up to remove any free water, and compressed into liquid form (liquefaction) and made ready for injection into depleted oil & gas wells for enhanced recovery thereby reducing the overall cost of carbon capture. The CCS deployments have stretched with 620 known projects in the technologically advanced countries of the sphere, with a aggregate of 400 Mtpa pipeline volume. The USA has maximum CCS projects, followed by the UK, Canada, Norway, and China. There are customized technologies available which can be fitted in Industrial plants with CCS or can be retrofitted into old plants for post combustion carbon capture for achieving net zero targets.

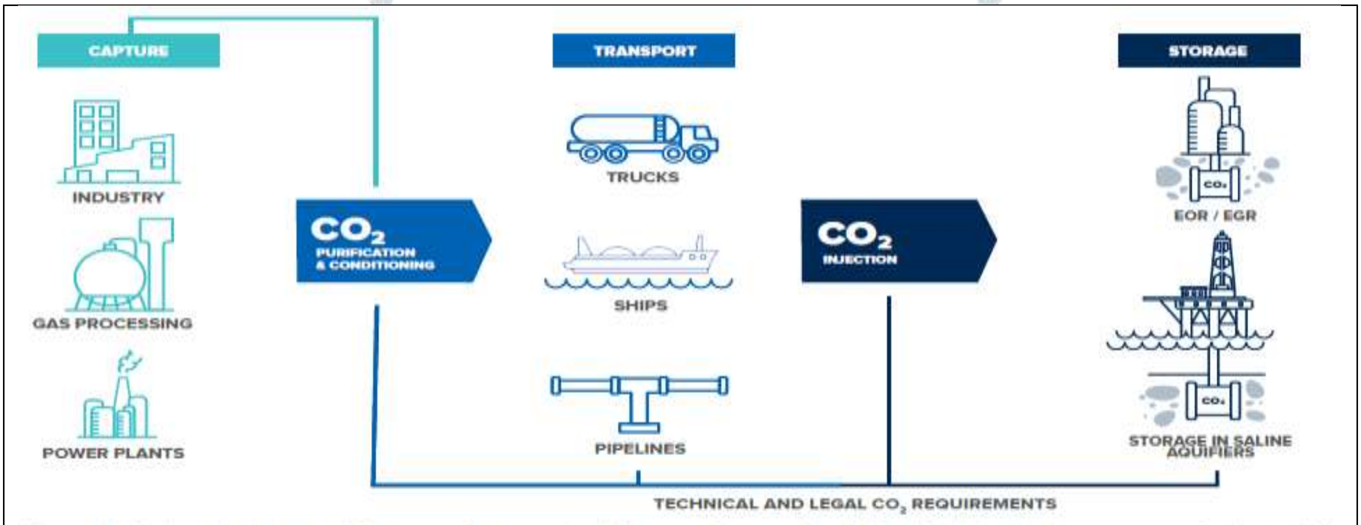

Figure 1 - Carbon Capture and Storage - A conceptual diagram. Source: The Global CCS Institute

CCS Technologies The carbon capture technology selected to capture CO_2 is generally determined by the feed stream properties and components, together with thoughts of energy, cost, and utility availability. The main technologies used for CO_2 capture are absorption, adsorption, membrane, cryogenics, solid looping, and inherent capture.

Absorption Technologies in an absorption process, CO_2 gas is chemically bonded into a liquid solvent to form a solution having uniform concentration. This solution is then pumped into a plant for de-absorption of CO_2 or regeneration of the solvent and the release of the CO_2 from the liquid solvent (Global CCS Institute, 2016). The solvents used in absorption of CO_2 capture are two types namely chemical and physical solvents. The Chemical solvents like MEA have reactive component that forms a chemical bond with CO_2 and gets converted into liquid form to allow it to be transported to the desorber, here to reverse the chemical reaction heat in the form of steam is applied to break the chemical bond and release the CO_2 through temperature swing. In case of Physical absorbents, the dissolution of CO_2 into the solvent is done through physical process of increasing the pressure, and CO_2 is held by Van der Waals forces without going into chemical bonding. Physical absorbents are regenerated by reducing the pressure of the solvent and vapor in contact with the solvent, resulting in the flashing of CO_2 into a gas through pressure swing. The Chemical solvents or absorbents are suitable for both conditions when partial pressure of CO_2 is high or low in the Flue gases streams. The physical absorbents are more effective in flue gases having high CO_2 partial pressures.

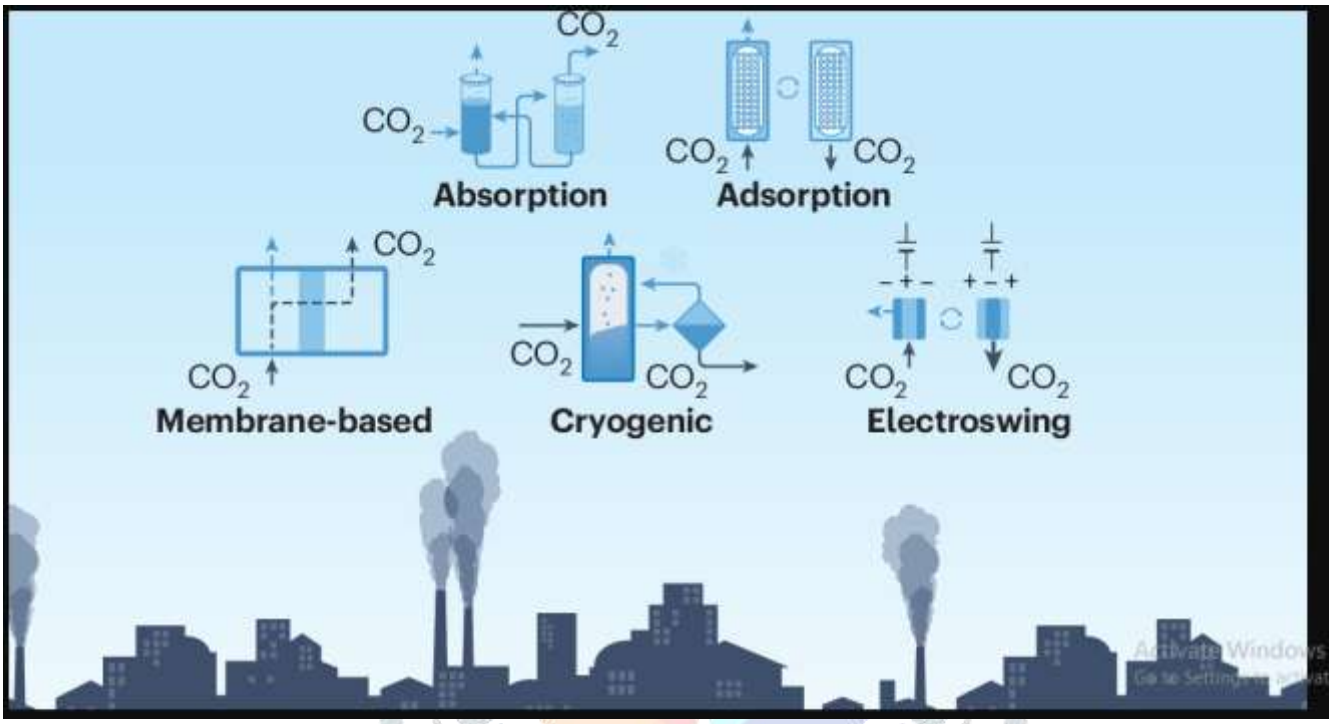

Fig-2 Absorption Technologies

Adsorbent Technologies Adsorbents are solid materials having binding sites on the surface of the sorbent to remove CO_2 preferentially from a gas stream. These materials generally have either a porous surface or granular structure having large surface area resulting in increased binding sites to capture CO_2 (Global CCS Institute, 2016). Chemical adsorption, is also known as chemisorption, solvents here binds the CO_2 with a chemical bond. This chemical bond is between the gas molecule and solid sorbent having surface quoted chemical solvents. The CO_2 bound in chemisorption is regenerated and released by heated steam through a temperature swing process by heating and reducing the temperature. The thermal energy in the form of steam is passed on a rich solvent in a de-absorber column where in overcomes the binding energy and liberates pure CO_2 from the flue gases. Physical adsorption, known as physisorption, binds the CO_2 with a weaker physical interaction known as Vander Waals forces. This weaker binding requires less energy to regenerate CO_2, and regeneration is generally based on a pressure swing mechanism where pressure of the vessel with the sorbent is raised and lowered. When the binding sites are fully occupied, the CO_2 can be released by either a reduction in pressure or increase in temperature. This swing in conditions will change the driving force of the environment to unbind CO_2 from the solid adsorbent, resulting in a higher concentration stream released from the adsorbent bed for further processing. Usually, at least two adsorber beds are alternated to ensure that there is always at least one bed available for capture, and the other can release the CO_2, though more beds can be deployed depending on stream requirements.

Membrane Technologies There are plenty of options available for using membranes for recovering CO_2 from flue gases A membrane is a semi-permeable barrier which separate a particular chemical constituents of a gas mixture based on their relative rates of mass transfer through the barrier or medium. For CO_2 capture plants, CO_2 would pass through the semi-permeable membrane the quickest compared with other molecules in the gas stream. Membrane separation primarily uses the partial pressure of CO_2 and the overall pressure of the inlet gas to drive the separation of CO_2 from the feed gas stream. Membrane separation is generally more favorable when there are higher partial pressures of CO_2 in the feed gas stream, and a higher overall inlet gas stream pressure to drive the movement of CO_2 across the barrier. In one such concept, flue gases are made to pass through a series of bundles of membrane tubes, while an amine solution is made to flow through the shell side of the bundle. The Carbon Dioxide (CO_2) shall pass through the membrane and get absorbed in the amine solution. In contrast, the impurities entry shall get blocked from the solvent amine, thereby reducing the amine loss due to stable salt formation as a product. By this means, we are achieving higher loading differential between comparatively rich amine and lean amine solvent. The amine solvent would be regenerated after leaving the membrane bundle, before getting recycled and re-energized. The chemically coated membranes have increased selectivity and permeability for the Carbon Dioxide (CO_2) getting filtered out from the flue gases. The membranes manufactured by the Solvent–Gel dip process are inorganic in nature having a microporous inorganic silica containing Amine functional groups for the separation of CO_2 from flue gases. In an another concept inorganic membranes are prepared from a silica membrane which have properties to selectively separate CO_2 from methane (CH4). By modifying the membrane, the strong interactions between the permeating CO_2 molecules and the amine functional membrane pores shall enhance selective diffusion of CO_2 along the pore wall of the membrane with subsequent blocking of the transport of other gases, such as O2, N2, and SO2. Thus, this novel membrane shall have much better CO_2 selectivity compared to a pure silica membrane, in-case right balance between permeability and selectivity can be achieved. Zeolite based membranes are crystalline Alumino-silicate based materials with well-defined sub-nanometer pores having unique surface properties. These membranes are perfect for molecular separations of CO_2 from flue gases. The Membrane Technology and Research (MTR) has developed novel thin-film composite polymer membranes to capture increased configurations of the flux of CO_2 across it, thereby reducing the required area. The membrane modules in the power plants are placed in such a way that an optimal configuration is achieved to maximize the driving force across it.

Cryogenic Technologies are CO_2 capture process referring to complete condensing of CO_2 from the other components of the flue gases. CO_2 have a different condensation point in comparison to other flue gas components, and this difference is used to extract CO_2 through compression, cooling, and condensing. The point of condensation for CO_2 is at temperatures well below ambient temperature and at elevated pressure to avoid the formation of "dry ice". This process generates liquid CO_2 as a part of the production process without further treatment; other CO_2 processing facilities that need to make liquid CO_2 for transport by road, rail, or ship will have a small cryogenic liquefaction unit after the main CO_2 capture facility. This cryogenic processes reliability is dependent on extremely low temperatures to separate CO_2 from flue gases, by taking advantage of differences in phase behavior of its constituents. At sufficiently low temperatures and appropriate pressures, CO_2 can be condensed into a liquid or directly frozen into a solid, while the major components of flue gases such as nitrogen and oxygen remain in the gaseous phase. This fundamental thermodynamic property forms the basis of cryogenic CO_2 capture. In cryogenic CCS systems, the gas stream is first pretreated to remove moisture and impurities that could otherwise freeze and block equipment. The dried gas is then cooled through a series of heat exchangers and refrigeration system. As the temperature drops below the CO_2 phase-change threshold, CO_2 is selectively separated either as a liquid (cryogenic condensation) or as a solid (cryogenic de-sublimation or anti-sublimation). The separated CO_2 is subsequently warmed, compressed, and conditioned for transport and long-term geological storage. Because the separation is purely physical, no chemical solvents are required, eliminating problems related to solvent degradation, corrosion, and solvent regeneration. One of the key advantages of cryogenic CCS is the ability to produce CO_2 with very high purity, often exceeding 99%. This makes the technology particularly attractive for applications where high-purity CO_2 is required, such as enhanced oil recovery, chemical synthesis, or pipeline transport. Cryogenic methods are especially well suited to gas streams that already contain relatively high concentrations of CO_2, such as those encountered in natural gas processing, hydrogen production via reforming, and certain industrial processes. In these cases, the energy penalty associated with refrigeration is more manageable, and the overall process efficiency improves.

Despite these advantages, cryogenic technologies face significant technical and economic challenges. The primary limitation is the high energy consumption required to achieve and maintain cryogenic temperatures, particularly when treating dilute post-combustion flue gases where CO_2 concentrations are typically below 10–15%. Additionally, managing the formation of solid CO_2 frost on heat exchanger surfaces presents operational challenges, as excessive buildup can reduce heat transfer efficiency and cause blockages. These factors have so far limited large-scale commercial deployment of cryogenic CCS for power plant applications. These challenges have been overcome through improved process design and integration. Advanced cryogenic carbon capture (CCC) concepts incorporate optimized heat recovery, staged cooling, and integration with waste cold or renewable electricity sources to reduce energy demand. Hybrid systems that combine cryogenic separation with membranes or adsorption technologies are also being explored to pre-concentrate CO_2 before deep cooling, thereby improving overall efficiency.

To recapitulate we can say that cryogenic technologies in CCS offers a solvent-free, high-purity option for CO_2 separation which is predominantly suitable for higher CO_2 strength gas streams and industrial applications. The high energy penalty at present dampen their extensive use in post-combustion power generation, with progressive advances in process integration, hybrid system design, and low-carbon electricity generation continue to augment their potential role in future low-carbon energy and engineering systems.

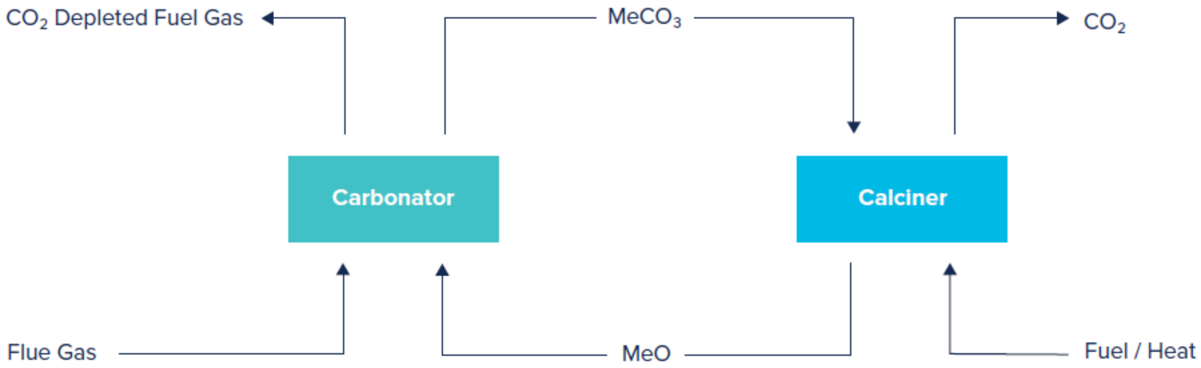

Fig-3 Solid Looping Process

Solid Looping Technologies utilizes solid materials as sorbents, which are oxygen carriers which cyclically react with carbon dioxide (CO_2) or oxygen in separate reactors. By constantly looping these solids between different process stages, CO_2 can be selectively captured, released in a condensed form for transportation and long-term storage. A solid looping carbon capture process consists of predominant use of metal oxide (MeO) or other solid re-generable composite such as metal carbonates (MeCO3) that can transport CO2 from a carbonator reactor to a calciner reactor, as shown in Figure 3 (Global CCS Institute, 2016). Solid looping systems are state of art CCS technology which integrates capture and regeneration in a thermally efficient manner those avoids many of the shortcomings related with liquid solvent-based skills. Calcium looping is extensively studied and developed solid looping approaches where calcium oxide (CaO) reacts with CO_2 in a carbonator reactor to form calcium carbonate ($CaCO_3$) which are heated to high temperatures, typically above 900 °C in a Calciner, causing the $CaCO_3$ to decompose back into CaO and a nearly pure CO_2 stream. Calcium looping is a choice of coal and gas fired power plants and cement manufacturing industries, as it utilizes inexpensive and abundant limestone-derived materials.

In comparison to conventional amine-based absorption, solid looping systems achieve lower energy penalties. They also reduce issues related to solvent degradation, corrosion, and wastewater generation. Solid looping processes can be integrated with existing industrial infrastructures, which are difficult to abate, such as cement kilns, steel plants, and refineries. Solid looping technologies still face challenges like sorbent deactivation due to sintering, attrition, or poisoning over multiple cycles which reduces capture efficiency and increase operating costs. Reactor design and solid handling at large scales also present engineering challenges, particularly in maintaining stable circulation and effective heat transfer.

Solid looping technologies offer a substantial contribution for CCS to provide lower-cost alternatives to conventional capture methods. Approaches such as Calcium looping, chemical looping combustion, and solid adsorption looping enable high-purity CO_2 capture with low energy penalties. As R & D efforts continue, solid looping technologies would have a critical role in the future deployment of CCS, predominantly in high-temperature industrial applications and large scale power generation systems.

Inherent Capture Technologies Inherent capture technologies or process refer to systems that produce high partial pressure CO_2 as an inherent part of the process. This stream of higher partial pressure CO_2 generally requires little to no additional work or energy to separate CO_2. Some chemical processes already inherently produce high partial pressure, high concentration CO_2 to make the desired chemical. This includes the fermentation of ethanol and the production of ethylene oxide. Extracting CO_2 from the process stream of hydrogen to produce ammonia also produces a high partial pressure of CO_2, though it tends also to contain other components. In other cases, innovative new technologies are being developed to generate high partial pressure CO_2 in power generation and industrial applications. Typical examples include the Allam-Fetvedt cycle and advanced calciners used for lime and cement manufacture.

The Allam-Fetvedt cycle has been proposed and demonstrated using CO_2 as the primary working fluid, with energy added to the system through the controlled addition of fuel and oxygen. The oxy-fuel combustion heats and pressurizes the CO_2 working fluid, from which energy is extracted through a turbine. To maintain mass balance, the produced water and a small portion of CO_2 is siphoned from the system.
In cement manufacturing, companies are exploring ways to heighten the partial pressure and concentration of CO_2 from cement plants, specifically calciners. Calciners are generally located at the entry point to kilns, where limestone (calcium carbonate) is decomposed by heating into lime (calcium oxide) and CO_2. Traditionally, methods use burners and hot air directly in contact with limestone, while new inherent capture methods keep the ground limestone separate from the heated gas, so the CO_2 produced is a greater proportion of the calciner exhaust gas and, therefore, easier to separate.

Research Gap and Problem Statement-The Copernicus Climate Change Service, 2024 data shows that the average earth surface air temperature is rising since 2023 seeing the first recorded days with temperatures 2°C above the reference preindustrial average temperature. When considering monthly averages, the average surface air temperature was at or above 1.5°C higher than the preindustrial average for 12 consecutive months from July 2023 to June 2024. To limit the long-term temperature, rise to well below 2°C and towards 1.5°C above the preindustrial average, in line with the Paris Agreement, greenhouse gas emissions must be reduced to net zero by the middle of this century, and carbon dioxide removal technologies must be commissioned to address the stocks of CO_2.

Methodology to address the above research gaps and problem statement connected with global temperature rise as per provisions contained in Paris Agreement various, options and technological innovations have been discussed in the previous paragraphs. Specifically, the CO_2 Capture using base solvent MEA is discussed in methodology amongst the portfolio of CO_2 capture methods. CO_2 capture facilities are modelled with a twin-column arrangement that exchanges solvent that are "rich" and "lean" in CO_2 between the columns. The absorber column is where CO_2 is separated from a gas stream by a reaction with MEA to form a "rich solvent". This solvent is then transferred to the desorber column, where heat is used to separate MEA and CO_2. "Lean solvent" or pure solvent are recovered from the bottom of the desorber, which are then recycled for use again in the absorber. This process, as well as the ancillary units, are outlined in Figure 4.

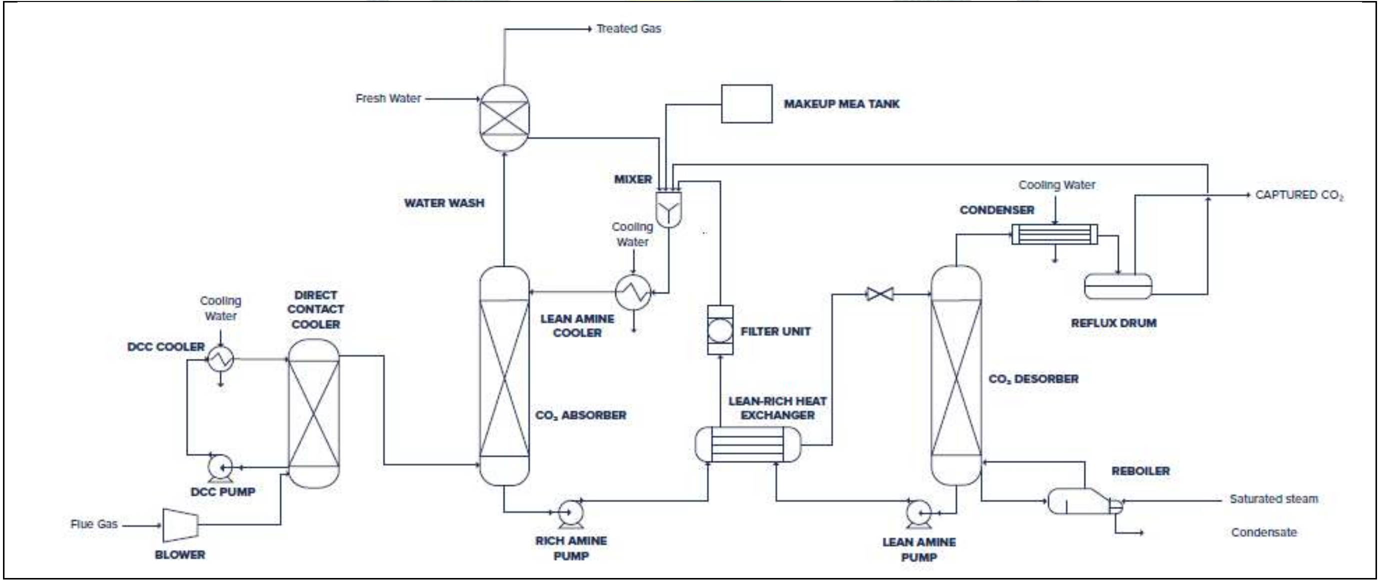

Figure 4 - Typical MEA Capture Plant Arrangement

Analysis of Chemical absorption of CO_2 using base solvent MEA-This analysis is based on chemical absorption of CO_2 using MEA as a base solvent on a standard dual column system integrated with cross heat exchanger between the lean and rich MEA solvent. An in depth study has been carried out using MEA as a base solvent to provide an insight into the current cost of carbon capture in various industries. MEA based chemical solvents, are the proven state of the art technology for carbon capture in post combustion installations specially power plants. The capture cost studied here does not include downstream CO_2 compression and upstream flue gas pretreatment to address any contaminants such as SOx or NOx, which increases the rate of amine degradation. The upstream pretreatment has been excluded in this study as it varies with types of industry, it's production process, and feedstock used. In this study flue gases used has been produced from combustion of supercritical pulverized coal to evaluate technical performance. The figure 4 refers to the process of carbon capture using MEA. The flue gases are initially sent through a blower to increase the stream pressure to overcome the pressure drop of the direct contact cooler (DCC) and the absorber these gases are then cooled in the direct contact cooler using a water wash. In order to remove SO2 prior to contact with MEA caustic scrubbing of flue gases are carried out. The cooled flue gases are fed at the bottom of the absorber column, which consists of packed beds in the absorption section. The flue gases move in counter current direction of movement of lean or pure solvent in absorber assembly to allow maximum absorption of CO_2.The flue gases leaving the CO_2 absorption section is scrubbed in the top water wash section and passes through a demister section to remove MEA or degraded solvent. The concentration of MEA leaving the water wash is less than 3 ppm (mol). The rich amine solvent is loaded with CO_2 leaves the bottom of the absorber, and is pumped through the rich amine pump to progress through the lean rich heat exchanger and to the operating pressure of the desorber. The rich amine enters the lean-rich heat exchanger and is heated by the relatively hot lean amine from the bottom of the desorber. The heated rich amine is then sent to the top of the desorber. The rich amine solvent is regenerated in the desorber column by heating from the reboiler at the base of the column. The reboiler supplies thermal energy via low-pressure steam. CO_2 is released from the rich amine as it is regenerated in the desorber and passes through a demister before heading out the top of the column to be condensed in the condenser with cooling water. The lean amine that has been created from regeneration is sent to the lean-rich heat exchanger and is partially cooled by the rich amine prior to the rich amine's entry to the stripper column. A filtration unit will also be present to remove any heat-stable salts and trace impurities. The partially cooled lean amine is then sent to the mixer, which combines with a partial flow of the condenser liquid, fresh makeup water and fresh MEA to maintain water and MEA balance. The combined lean amine from the mixer is then cooled a final time in the lean cooler to reduce the temperature before re-entry to the absorber.

Process Modelling & Boundaries: When modelling CO_2 capture facilities, the level of detail and host site integration can affect the overall model output. In the modelling completed for this report, the following boundaries were kept.

Flue gas pretreatment: Beyond the blowers and direct contact coolers (DCC) units, other forms of pretreatment were excluded from the analysis as different flue gas streams require different pretreatment. For instance, cement plants require dust treatment to address dust production in the cement process; natural gas combined cycle plants do not produce dust and therefore do not require treatment.

Utilities and site integration: Sufficient utilities are assumed to be available for simplicity of modelling, and the modelling of boilers and cooling towers to supply steam and cooling water respectively are excluded.

Downstream flue gas treatment: Treatment of the CO_2 depleted flue gas stream after the water wash was not modelled in some areas, certain limits on emissions to air may require further treatment, though the exact limits will vary. The modelling completed ensured that the levels of amine emitted to the atmosphere remained below 3 ppm (mol), and generally other notifiable pollutants are dealt with in pretreatment before the CO_2 capture plant as most have an impact on the efficient operation of a CO_2 capture plant.

Process Modelling Key Assumptions There are a significant number of design decisions that impact the overall process and associated costs of a CO_2 capture plant. Adjusting even only a few of these values results in a wide range of potential designs and systems. In the modelling completed for this report, the following design assumptions were made for this case study:

- Where not mentioned, the capture fraction is 90% capture of CO_2 across the absorber.
- The lean solvent sent to the absorber is controlled to 30 weight % MEA.
- Inlet flue gas contains 13.7 mol% CO_2 at a temperature of 55°C and a pressure of 5 kPag.
- Minimum approach temperature of 10°C across the heat exchanger inlets and outlets.
- Condensed liquid from the desorber directed to the Mixer and not back to the desorber as reflux, due the condensed stream primarily being composed of water (known as Desorber Condensate Bypass).
- Utilities, including low-pressure steam, are available in sufficient quantities to provide the required energy to the CO_2 capture plant.

- The modelled CCS facility has a specific reboiler duty of between 3.5 and 3.8 GJ per tonne of CO_2. Further optimization of MEA systems can be completed, or proprietary solvent mixtures may be used, as specific reboiler duties of between 2.0 and 3.5 GJ per tonne of CO_2 have been reported by CO_2 capture technology vendors (Global CCS Institute, 2024a).

Results and Discussions on selection of technologies to address the problem statement Before we understand the cost involved in Carbon Capture, underneath in tabular form are given the TRL. Established CO_2 capture technologies have been deployed in sectors such as natural gas treatment, fertilizer production, and ethylene oxide manufacturing for decades. These industries necessitate the removal of CO_2 from their processes to manufacture their product. Further, in the United States over 100 CO_2 suppliers capture CO_2 from existing industrial gas streams, which are supplied for utilization (US EPA, 2024). Current advancements stem from the novel applications of CO_2 capture technology on sources such as low partial pressure CO_2 feed gas or from more novel flue gases such as cement and waste to energy. The variety of potentially applicable technologies reflects the variety of flue gas streams which could be captured from, and the limitations and cost drivers in each individual host site. Table 1 provides an updated overview and assessment from our previous work, incorporating information provided to the Global CCS Institute's 2024 Technology Compendium (Global CCS Institute, 2024a). Comparative technological chart in tabular form for TRL assessment years 2020 and TRL assessment year 2024 are discussed below with Technology Category and type of technologies used.

Table 1 - TRL Assessment of CO_2 capture technologies commercially available or under development. TRL 2020 Assessment from Technology Readiness and Costs Report (Global CCS Institute, 2021)

CATEGORY	TECHNOLOGY	2020TRL ASSESSMENT	2024 TRL ASSESSMENT	DETAILS
Chemical Absorption	Amine based Solvents	9	9	Widely used in fertilizer, soda ash, natural gas processing plants, e.g. Sleipner, Snohvit, and used in Boundary Dam
	Hot Potassium Carbonate (HPC)	9	9	Fertilizer plants, e.g. Enid Fertilizer
	Sterically hindered amine	6-9	6-9	Demonstration to commercial plants, depending on technology provider
	Carboxylic Acid based solvent	6-7	6-7	Pilot tests to demonstration plant feasibility studies
	Chilled Ammonia Process	6-7	6-7	Pilot tests to demonstration plant feasibility studies
	Phase change Solvents	5-7	6-7	DMX™ Demonstration
	Water-Lean Solvent	4-7	6-7	Pilot test and commercial scale FEED studies: Gerald Gentleman Station carbon capture plant, the Jinjie pilot plant
	Amino Acid based solvent /Precipitating Solvents	4-5	4-5	Lab test to conceptual studies
	Ionic Liquids	4-5	4-5	Pilot tests
	Encapsulated solvents	2-3	2-3	Lab tests

Physical Absorption	Physical Solvents	9	9	Widely used in natural gas processing, coal gasification plants; e.g. Val Verde, Shute Creek, Century Plant, Coffeyville Gasification, Great Plains Synfuels Plant, Lost Cabin Gas plant
Enzyme based absorption	Enzyme Catalysed Absorption	6	7-8	Commercial demonstration facility in Quebec
Solid Adsorbent	Pressure Swing Adsorption/Vacuum Swing Adsorption	9	9	Port Arthur SMR VPSA
	Temperature Swing Adsorption	5-7	6-7	Kern River Pilot
	Sorbent-Enhanced Water Gas Shift	5	5	Pilot tests, e.g. STEPWISE
	Electrochemically Mediated Adsorption	2-3	2-3	Lab testing
Membrane	Gas separation membranes for natural gas processing	9	9	Santos Basin Pre-Salt Oil Field CCS
	Polymeric Membranes	7	7	FEED studies for large pilots
	Electrochemical membrane integrated with Molten Carbonate Fuel Cells	7	8	Large pilots at Plant Barry, demonstration plant in South Korea
	Polymeric Membranes / Cryogenic Separation Hybrid	6	6-8	Demonstration plants and pilot studies
	Polymeric Membranes/ Solvent Hybrid	4	4	Conceptual studies
	Room Temperature Ionic Liquid (RTIL) Membrane	2-3	2-3	Lab testing
Solid Looping	Calcium Looping (CaL)	6-7	7-8	STRATOS plant in Texas (0.5 Mtpa) is under construction
	Chemical Looping Combustion	5-6	5-6	Pilot test at ALSTOM's existing Multipurpose Test Facility (3 MWth) and at a technical university in Germany
Inherent Capture	Allam-Fetvedt Cycle	6-7	6-7	50 MW demonstration plant in La Porte
	Lime Processing Kilns	5-6	6-7	Leilac-1, with Leilac 2 under development
Electrolysis	Electrodialysis of Oceanwater	6	6-7	Ongoing field trials

Cryogenic Separation	Cryogenic Distillation	9	9	Deployed on various projects around the world

Carbon Capture Costs The costs of CCS can vary widely depending on a range of project-specific factors, in addition to overall trends. Generally, across the CCS value chain, the costs associated with capturing the CO_2 make up the greatest proportion of the overall costs, followed by transport and then storage, though the cost proportions may vary dependent on the project Capture cost factors primarily relate to the properties of the stream from which the CO_2 is separated. This includes the concentration of CO_2 in the stream, the pressure, and the overall volume of CO_2 to be captured. Economies of scale especially play a role in CCS projects, where capital costs can be very significant. The underlying technology used to capture CO_2, as well as the targeted CO_2 capture percentage, energy and cooling costs, plant location and any necessary pretreatment of the inlet stream to the capture plant, all have an impact on the overall cost to capture CO_2.

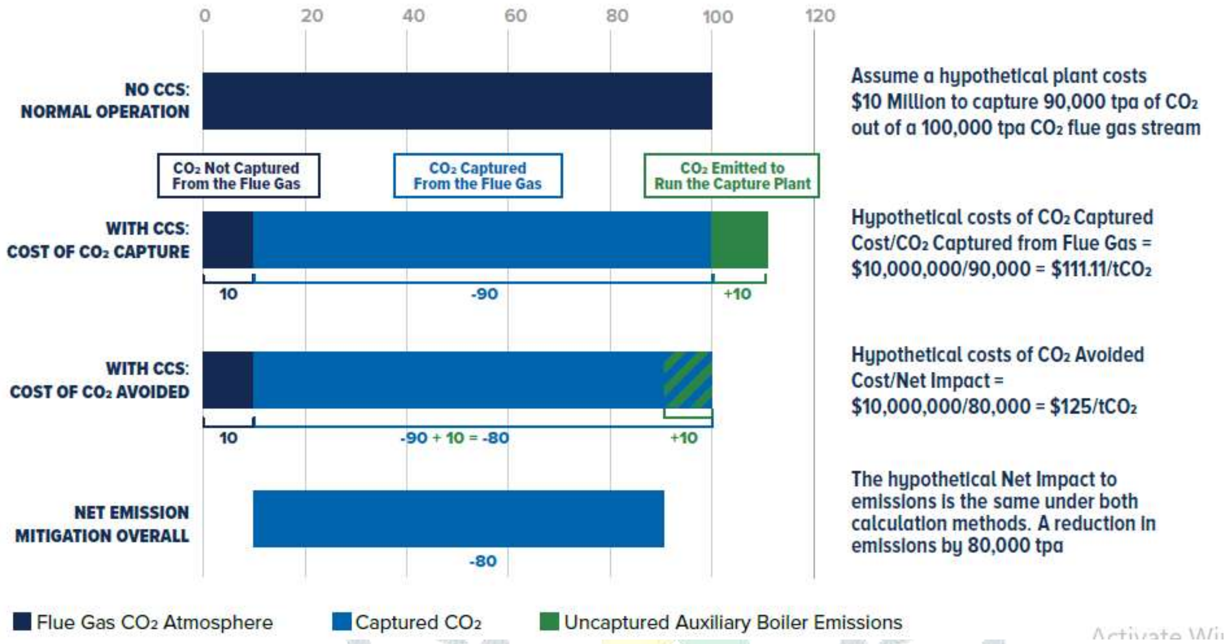

Figure 5 - Visualization of the CO_2 flows and costs associated with a CO_2 capture

Cost of CO_2 Captured Vs Cost of CO_2 Avoided. The per-unit costs for CO_2 capture plants are often either referred to in the form of Cost of CO_2 Captured or Cost of CO_2 Avoided. The terms are similar but have an important difference when calculating the costs and capacities of the process, including the emissions related to the operation of the plant. The cost of CO_2 captured is the total annualized cost of a CO_2 capture plant divided by the total CO_2 captured by the plant (the output CO_2 stream). The cost of CO_2 avoided is the total annualized cost of a CO_2 capture plant divided by the total of CO_2 captured by the plant (the output CO_2 stream) less the CO_2 emitted to run the plant. CO_2 emissions to run the plant include burning fuel to make steam and the emissions associated with electricity from the grid, which are generally what would be considered Scope 1 & 2 emissions in a lifecycle analysis.

Capital Costs and Operating Costs in a CO_2 Capture Facility A standard MEA plant is used to illustrate a potential distribution of costs within the capture process. Different technologies combined with different inlet feed streams to a capture plant will change the estimated capital and operating costs and the distribution between them both.

Capital Costs in a carbon capture facility relate to the fixed, one-time expenses involved in building the facility. Capital costs correlate with the size of the facility capturing CO_2. The units with the largest impact on capital costs are the columns, such as the absorber, desorber, water wash, & direct contact cooler, as well as the heat exchangers, such as the lean-rich heat exchanger, the condenser and the reboiler. Other pieces of equipment, such as the blower, pumps, piping, and electrical & instrumentation equipment, will also factor into the overall capital cost of the capture plant. Capital equipment like the columns and the flue gas ducting can be seen in Figure 6, which includes the flue gas ducting, the absorber tower and the desorber tower. This image is of the Just Catch plant installed by SLB Capturi at the Twence CCU and is capable of capturing 100 ktpa of CO_2. As a rule of thumb, the diameter of columns increases with more gas flowing through the column. The height of a column tends to be determined by the level of separation required, or in the case of CO_2 capture plants, the percentage of CO_2 captured from the inlet stream. Outside of equipment, there are also capital costs associated with the land that is to be purchased (if this is a greenfield site), the engineering, procurement, and construction costs, and the costs involved with ownership of a site, such as startup costs, inventory requirements, and financing costs.

Figure 6 - Twence CCU in Hengelo, The Netherlands. Image courtesy of SLB and Aker Carbon Capture JV

Figure 6 - Capital Costs

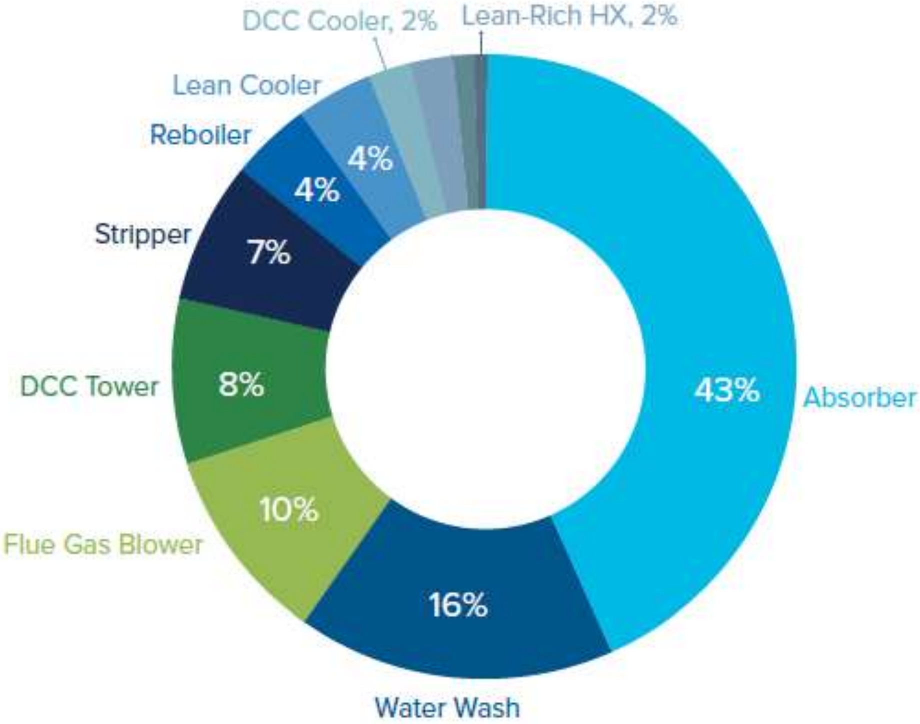

Figure 7 – Breakdown of Capital Costs

Operating Costs, the operating costs of a typical MEA CO_2 capture plant are the costs involved in running the plant. The majority of that cost is associated with the regeneration of the amine solvent. Regeneration of the solvent in the CO_2 desorber involves heating the solvent. This heating is usually completed by heat exchange in the reboiler between the CO_2 rich solvent and typically low-pressure steam. The rich solvent is generally preheated by the hot lean solvent exiting the bottom of the column. The amount of thermal energy, and therefore the amount of steam required, varies due to solvent composition, the heat capacity of the solvent, the loading of the solvent with CO_2 and the binding strength of the solvent with the CO_2. Cooling systems are also necessary to remove heat from the lean amine prior to the absorber, in the condenser, and in the direct contact cooler. In addition to thermal energy requirements, electrical energy is required to drive blowers, pumps, and compressors within the capture plant. An amount of "makeup" water and amine must also be added to the capture plant while it operates, as a portion is lost in the process of capturing CO_2 from the inlet gas. Makeup amine must be added to the system as, over time, the solvent will degrade due to repetitive thermal cycles and oxygen exposure. Flue gas contaminants that slip past the pretreatment system will, over time, also degrade the amine. This degraded amine must be removed and replaced with fresh solvent to maintain the required operational capabilities of the plant. These costs are in addition to the required operating and maintenance labour costs, administrative support, insurance and local taxes and fees that are incurred on a fixed basis (i.e. they do not vary with plant operation).

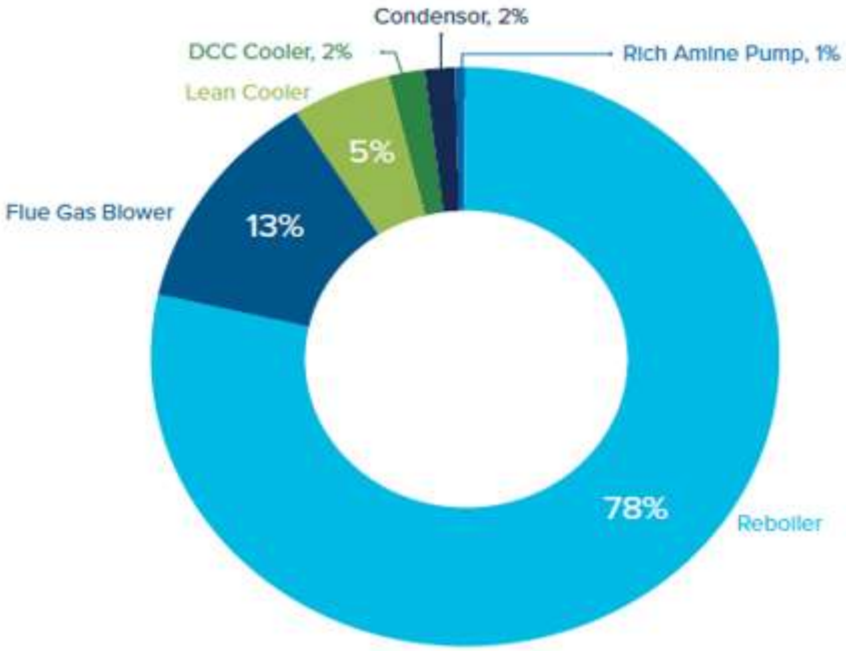

Figure 8 – Breakdown of Variable Operating Costs of MEA Plant

Conclusion The rapid industrial growth has led to excessive use of carbon rich fossil fuel for combustion to meet the rising demand of energy around the globe. TRL- Technology Readiness Level has been displayed in table-1 for years TRL 2020 and TRL 2025.The type of technology to capture carbon dioxide is explained in Tabular form in Table-1. This paper has adequately covered the various technological advancements for Capturing Carbon and has delved into CO_2 capturing cost and CO_2 avoidance cost. The cost component brought out in this paper pertains to of carbon capture process only, the transportation and compression related costs is not within the purview of this paper, the same will form part of different study.

References

1. Air Products. (2024). Clean Hydrogen Production. https://www.airproducts.comenergy-transition clean hydrogen-production

2. Appl, M. (2011). Ammonia, 2. Production Processes. In Ullmann's Encyclopedia of Industrial Chemistry. Wiley. https:// doi.org/101002/14356007.o02 o11

3. Bond, S. (2024). Ship Design for CO_2 Transportation.
4. Chang, M. H., Chen, W. C., Huang, C. M., Liu, W. H., Chou, Y. C., Chang, W. C., Chen, W., Cheng, J. Y., Huang, K. E., & Hsu, H. W. (2014). Design and Experimental Testing of a 1.9MWth Calcium Looping Pilot Plant. Energy Procedia, 63, 2100–2108 https://doi.org/10.1016 jegypro.2014.11.226

5. Clarksons. (2022). Liquid CO_2 carriage by sea: Market movements. https://www.clarksons.com/ home/news-and insights/2022/liquid-CO_2-carriage-by-sea-market movements.

6. Copernicus Climate Change Service. (2024, July 10). June 2024 marks 12th month of global temperatures at 1.5°C above pre-industrial levels https:/climate copernicus. eu/june-2024 -marks-12th-month-globaltemperatures-15degc-above-pre-industrial-levels

7. Core Energy Group (2015). Gas Production and Transmission Costs Eastern and South Eastern Australia.
8. Cost Data On Line, Inc. (2024). International Cost Factor CD Manual.

9. Deng, H., Roussanaly, S., & Skaugen, G. (2019). Techno-economic analyses of CO_2 liquefaction: Impact of product pressure and impurities. International Journal of Refrigeration, 103, 301–315. https://doi.org/10.1016/j.ijrefrig.2019.04.011

10. DNV. (2024a). CETO: Pioneering low-pressure CO_2 shipping. https://www.dnv.com/article/expert-viewpoint-cetopioneering-low-pressure-CO_2-shipping/

11. DNV. (2024b). Positive outlook for carbon shipping amid big push to solve technical challenges. https://www.dnv.com/expert-story/maritime-impact/positive-outlook-for-carbon-shipping-amid-big- push-to-fix-technical challenges/

12. Drioli, E., Barbieri, G., & Brunett, A. (2018). Membrane Engineering for the Treatment of Gases.

13. Element Energy. (2018). Shipping CO_2 – UK Cost Estimation Study.

14. Fine, N. (2024, August 7). The Proof is in the pilots: Project Enterprise update. 2024 FECM Annual Project Review Meeting. https://netl.doe.gov/sites/default/files/netl-file/24CM/24CM_PSCC_7_Fine.pdf

15. Fluor. (2024). Econamine FG Plus Experience List.In Unpublished, contact Fluor directly for list
.
16. Global CCS Institute. (2016). The Global Status of CCS 2016 - Volume 3: CCS Technologies.

17. Global CCS Institute. (2021). Technology Readiness and Costs of CCS. https://www.globalccsinstitute.com/wpcontent/ uploads/2022/03/CCE-CCS-Technology-Readiness-and-Costs-22-1.pdf

18. Global CCS Institute. (2024a). State of the Art: CCS Technologies 2024. https://www.globalccsinstitute.com/wpcontent uploads/2024/08/CCS-Technologies-Compendium-2024-08-16-1.pdf

19. Global CCS Institute. (2024b). The Global Status of CCS: 2024.