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# The Role of CCUS in a Low-Carbon Future: A Critical Review

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**Abstract**

**With global $CO_2$ emissions continuing to rise, driving concerning rates of climate change, carbon capture, utilization, and storage (CCUS) technologies have attracted renewed interest for their potential to reduce atmospheric greenhouse gas levels. This review provides a wide-ranging overview of current and emerging approaches to CCUS. Fundamental concepts in CCUS, including pre-combustion capture, post-combustion capture, oxyfuel combustion, and $CO_2$ mineralization are discussed. The spectrum of technologies available for transporting, utilizing, and storing captured $CO_2$ is then explored. The use of pipelines, ships, rail, and trucks for moving compressed or liquefied $CO_2$ has been examined for transportation. Potential utilization options include enhanced oil recovery, fuel synthesis, microbial conversion, and mineral carbonation. Analysis of geological sequestration in saline aquifers and depleted oil/gas reservoirs, ocean storage, and mineral carbonation has been done for storing $CO_2$. The maturity level, costs, scalability, and technical feasibility of different CCUS technologies have been outlined. Critical challenges highlighted include the energy-intensive nature of current capture processes, infrastructure needs for transport and storage, and costs. This review synthesizes current technical knowledge on CCUS to identify the most promising approaches to reducing atmospheric $CO_2$ levels cost-effectively. It is then concluded by identifying critical research priorities, including improving capture efficiency, developing robust storage site assessments, monitoring technology, using captured $CO_2$ for sustainable products, and accelerating adoption through policy incentives. If global multi-disciplinary efforts are taken, CCUS can play a significant role in achieving carbon-neutral energy systems worldwide. This review provides a framework for understanding the current state of CCUS that can guide researchers and policymakers in advancing the deployment of CCUS technologies to areas where they hold the most potential to combat climate change.**

**Keywords - Carbon capture, $CO_2$ utilization, $CO_2$ storage, climate change mitigation, carbon neutrality**

## 1. Introduction

### 1.1 Sources of $CO_2$ Emissions

Carbon dioxide is emitted from both natural sources as well as human sources. Natural sources include decomposition, ocean release and respiration. In addition to the burning of fossil fuels like coal, oil, and natural gas, human sources include the production of cement, deforestation, oil refining, and emissions from various chemical industries. The three types of fossil fuels that are used the most are coal, natural gas and oil. Coal is responsible for 43% of carbon dioxide emissions from fuel combustion, 36% are produced by oil and 20% by natural gas.[11] The three main economic sectors that use fossil fuels are: electricity/heat, transportation and industry. Due to human activities, the atmospheric concentration of carbon dioxide has been rising rapidly since the Industrial Revolution and has now reached dangerous levels not seen in the last 3 million years. To prevent the continuous release of $CO_2$ from these facilities, cost-effective technologies for separating and capturing carbon emissions are needed.[11] Applying carbon capture at large point sources before the $CO_2$ is released into the atmosphere can significantly reduce emissions across the power generation and industrial sectors. Studies have estimated that pairing carbon capture systems with fossil fuel plants could reduce emissions from these facilities by up to 90%.[1] Currently CCUS is gaining global attention as a critical technology for achieving net-zero emissions by 2050. A recent estimate by International Energy Agency suggests that CCUS could capture and store up to 2.5 gigatons of $CO_2$ annually by 2030.

### 1.2 Carbon Capture and Storage

The United Nations Climate Change conferences, also known as Conference of the Parties (COP), are annual meetings of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC).[18] The first COP was held in Berlin in 1995 and since then, COPs have been held annually in different countries around the world. The COPs are important because they bring together governments, businesses, and civil society to discuss and negotiate actions to address climate change. The COPs have also been responsible for some of the most important international climate agreements, such as the Kyoto Protocol and the Paris Agreement.[27]

CCS (or carbon capture and sequestration) is the process of capturing waste carbon dioxide ($CO_2$) from large point sources, such as fossil fuel power plants, transporting it to a storage site, and depositing it where it will not enter the atmosphere, normally an underground geological formation. There exist several methods to separate $CO_2$ from industrial gases such as absorption, adsorption and membrane separation. Carbon capture and storage (CCS) has been emphasized on at several COPs, but it was particularly prominent at COP26 in Glasgow, Scotland in 2021.[18] At this COP, there was a strong recognition of the need for CCS to be part of the global effort to combat climate change.[27]

Currently CCUS is gaining global attention as a critical technology for achieving net-zero emissions by 2050. A recent estimate by the International Energy Agency suggests that CCUS could capture and store up to 2.5 gigatons of $CO_2$ annually by 2030.

### 1.3 Large Scale CCS Plants

CCUS plays an important role in reducing emissions and in carbon dioxide removal and there are various large-scale facilities built across various countries for CCUS technologies. Currently there are 51 CCS facilities globally – 19 in operation, 4 under construction, and 28 in various stages of development with an estimated combined capture capacity of 96 million tonnes of $CO_2$ per annum. The largest CCS facility in the world is the Shute Creek Gas Processing Plant in the United States, with a carbon capture and storage capacity of 7 million metric tons per year. Some of the largest CCS projects in operation worldwide, along with their carbon dioxide capture in million metric tons per year are mentioned in table 1.1.

| **Project Name** | **Country** | **Carbon Dioxide Capture Capacity (million metric tons per year)[8]** |
|---|---|---|
| Petrobras Santos Basin Pre-Salt Oil Field CCS | Brazil | 7 |
| Shute Creek Gas Processing Plant | United States | 7 |
| Century Plant | United States | 5 |
| Gorgon Carbon Dioxide Injection | Australia | 4 |
| Great Plains Synfuels Plant and Weyburn-Midale | United States | 3 |
| Qatar LNG CCS | Qatar | 2.2 |
| Alberta Carbon Trunk Line (ACTL) with North West Redwater Partnership's Sturgeon Refinery $CO_2$ Stream | Canada | 1.6 |
| Quest | Canada | 1.3 |
| Sleipner $CO_2$Storage | Norway | 1 |
| Air Products Steam Methane Reformer | United States | 1 |
| Sinopec Qilu-Shengli CCS | China | 1 |
| Illinois Industrial Carbon Capture and Storage | United States | 1 |

**Table 1.1** Largest CCS plants around the world

### 1.4 Carbon Credits and Carbon Markets

The concept of carbon credits was developed in the 90s when the climate change crisis began to loom large over the heads of various countries. The carbon credits system was officially set up in 1997 as part of the first international agreement to bring down emissions, i.e., the Kyoto Protocol and its mechanism were further established in the Marrakesh Accords.

Carbon credits are tradable certificates representing one metric ton of carbon dioxide ($CO_2$) equivalent emissions that have been avoided or removed from the atmosphere. They are used as a market-based mechanism to reduce greenhouse gas emissions and combat climate change.

Carbon markets are platforms where carbon credits are bought and sold. These markets create a financial incentive for companies and individuals to reduce their emissions. By purchasing carbon credits, entities can offset their own emissions, while those who generate or remove emissions can sell their credits to generate revenue.

There are two types of carbon markets. Compliance carbon markets are regulated by governments or international organizations and are mandatory for certain industries or emitters. Examples include the European Union Emissions Trading System (EU ETS) and the California Air Resources Board (CARB) Cap-and-Trade Program. Voluntary carbon markets are not regulated and participation is voluntary. They allow individuals and organizations to offset their emissions beyond any regulatory requirements. Carbon credits and carbon markets provides several benefits including cost-effective emission reduction by allowing entities to find the cheapest emission reduction options. They also facilitate flexibility and innovation in emission reduction technologies and practices. Carbon markets can operate across borders, enabling global cooperation in climate change mitigation.

## 2. Rationale and Importance of $CO_2$ Capture

### 2.1 Net Zero Emission 2050 Plan

The Net Zero Emissions by 2050 Scenario (NZE Scenario) is a normative scenario that shows a pathway for the global energy sector to achieve net zero $CO_2$ emissions by 2050, with advanced economies reaching net zero emissions in advance of others. This scenario also meets key energy-related Sustainable Development Goals (SDGs), in particular universal energy access by 2030 and major improvements in air quality. It is consistent with limiting the global temperature rise to 1.5°C (with at least a 50% probability), in line with emissions reductions assessed in the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report.[8] There are many possible paths to achieve net zero $CO_2$ emissions globally by 2050 and many uncertainties that could affect any of those pathways; the NZE Scenario is therefore a path, and not the path to net zero emissions.[8]

| **Country** | **Carbon Footprint ($GtCO_2e$)**[8] |
|---|---|
| China | 10.67 |
| United States | 5.42 |
| India | 2.65 |
| Russia | 1.71 |
| Japan | 1.16 |
| Germany | 0.8 |
| Iran | 0.73 |
| Indonesia | 0.69 |
| Canada | 0.62 |
| Brazil | 0.57 |

**Table 2.1** Top 10 countries with the highest carbon footprint

Table 2.1 shows the top 10 countries with the highest carbon footprint. These countries account for over half of the world's total carbon emissions. China is the world's largest emitter, followed by the United States and India. The majority of these emissions come from the burning of fossil fuels for electricity generation, transportation, and industrial processes.[3] These countries will not be able to reach carbon neutrality only by reducing their domestic emissions. They will need to offset much of their carbon footprint on international carbon markets. Reducing carbon emissions is essential to mitigate climate change. Countries around the world are taking steps to transition to clean energy sources, improve energy efficiency, and reduce deforestation.[3]

### 2.3 Indian vs. Global Scenario

India is the third largest carbon emitter and it also has the largest potential to reduce its carbon emissions up to 45% by 2030. This would make India a global leader in climate action. India is heavily reliant on coal for power generation which is a major source of CO2 emissions.3 However, the Indian government has recognized the need for CCS and it has set a target of capturing 100 million tonnes of CO 2per year by 2030. India's carbon emission plan aims to achieve net-zero emissions by 2070.3 The plan mainly focuses on decarbonizing key sectors such as energy, industry, transportation, and agriculture. But compared to the global scenario India is still lacking. CCS is still in its early stages of development in India and the availability of financial resources is limited while developed countries have more financial resources to invest in CCS. CCS is also perceived as safe and effective in developed countries. Despite these challenges, the Indian government is committed to developing CCS and many private sector Indian companies are also developing CCS projects.

## 3. $CO_2$ Capture Technologies

Carbon dioxide capture technologies are essential to decarbonize significant greenhouse gas emission point sources like fossil fuel power plants, cement production facilities, steel mills, and oil refineries. To mitigate the release of $CO_2$ from these stationary sources, various capture strategies have been developed and exhibited, ranging from pre-combustion plans to post-combustion systems, oxyfuel combustion techniques, and more emerging concepts. Both pre-combustion approaches, which act on the syngas fuel stream before combustion, and post-combustion methods, which separate $CO_2$ from flue gas exhausts, have been applied at pilot and demonstration scales. Even though these capture systems are technically possible, they need help with complicated integration, high costs, and high energy requirements. Innovative techniques utilizing microalgae, enzymes, or artificial photosynthesis may offer efficiency improvements in the future but are currently in the early stages of development and have limited scale-up potential. Overall, while a variety of $CO_2$ capture options exist, additional innovation and pilot deployments are essential to determine optimal technologies for large-scale demonstration and commercialization across a range of stationary emissions sources in power, cement, steel, and other heavy industries.

### 3.1 Pre-combustion $CO_2$ Capture

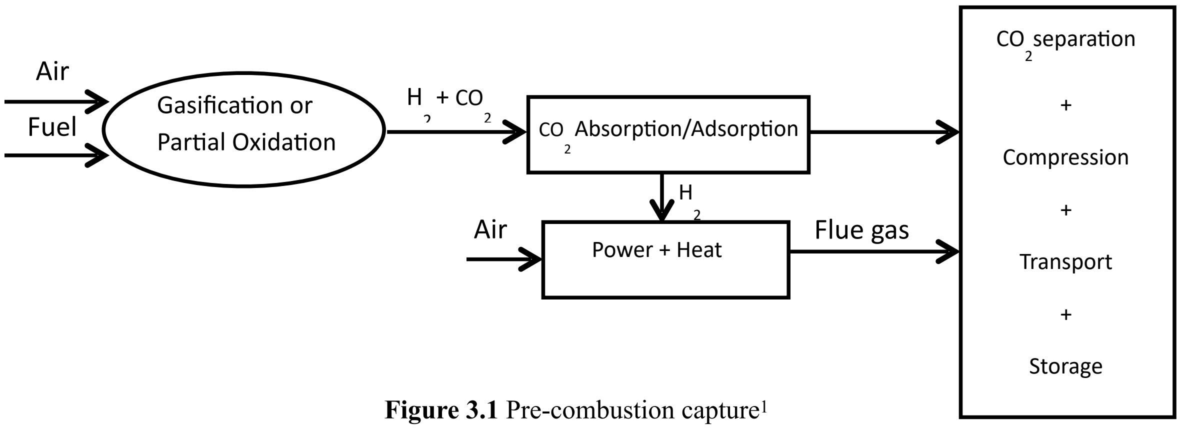


**Figure 3.1** Pre-combustion capture[1]

Pre-combustion capture involves the initial conversion of solid or liquid fossil fuels like coal and natural gas into synthesis gas (syngas), which is a mixture of carbon monoxide (CO) and hydrogen ($H_2$) through processes like gasification or steam reforming. The syngas is then reacted with steam in a catalytic shift converter to produce $CO_2$ and additional H2. The $CO_2$ can then be separated from the syngas stream before final combustion, resulting in a relatively pure, concentrated stream of $CO_2$ ready for subsequent transport and storage.[1,2] There are several leading technology types for pre-combustion $CO_2$ capture, including the Selexol process, which uses a dimethyl ether of polyethylene glycol solvent. The Rectisol process uses chilled methanol, the Purisol process uses N-methyl-2-pyrrolidone, and the Fluor Daniel Econamine FG process uses diglycolamine. Compared to post-combustion capture, pre-combustion can offer potential efficiency gains in power generation cycles by producing a stream of nearly pure hydrogen for combustion.[13] However, pre-combustion capture faces challenges related to the high costs and complexity of integrating the gasification and shift conversion steps with the $CO_2$ separation and power generation systems. Figure 3.1 shows a basic flow diagram for pre combustion. Additional technical hurdles include the selection of optimal solvents and processes, achieving effective heat integration, and scaling up from small demonstration units

### 3.2 Post-combustion $CO_2$ Capture

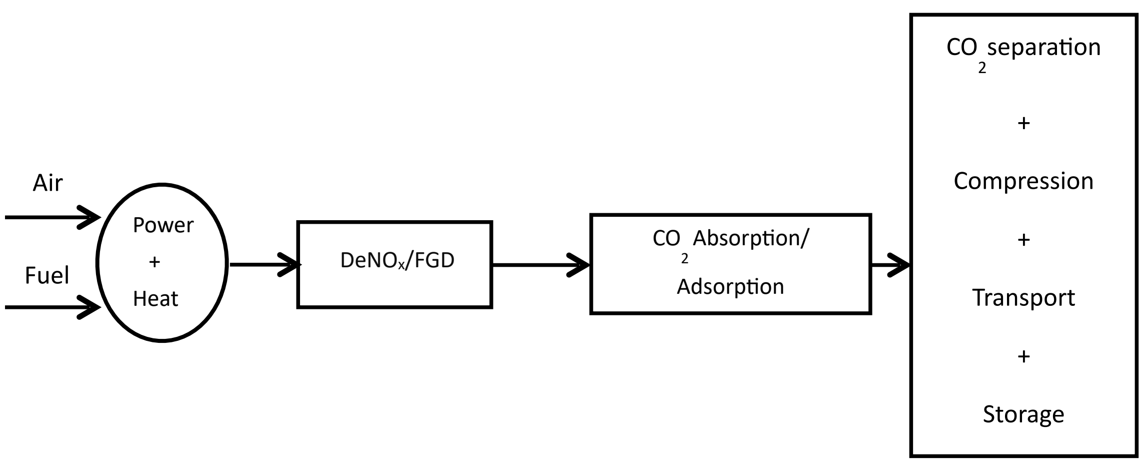

**Figure 3.2** Post-combustion capture[1]

In post-combustion capture, the $CO_2$ is separated from flue gas exhaust stacks after the fossil fuel has been combusted in the air. The technology used in this approach can be retrofitted to existing power plants to minimize emissions. Post-combustion capture typically relies on amine-based chemical absorption solvents like aqueous monoethanolamine (MEA) solutions to selectively absorb $CO_2$ from the flue gas stream.[2,5] The most widely demonstrated approach is to use MEA scrubbing in an absorption/desorption loop to produce a pure $CO_2$ stream for subsequent storage and a return gas low in $CO_2$ for release.[2] Post-combustion capture accounts for most existing $CO_2$ capture installations in power generation facilities.[1] Besides chemical absorption with amines, other post-combustion capture techniques include physical solvent scrubbing, adsorption onto solid media like activated carbons, cryogenic fractional distillation, and selective membranes.[2,5] However, the high energy requirements for solvent regeneration and various solvents' limitations remain key challenges facing post-combustion capture. Table 3.1 compares some key parameters of pre-combustion and post-combustion $CO_2$ capture systems:

| **Parameter** | **Pre-combustion[1,8]** | **Post-combustion[1,8]** |
|---|---|---|
| Typical $CO_2$ capture efficiency | 80-95% | 85-95% |
| Primary $CO_2$ separation process | Gas absorption with solvents | Chemical solvent scrubbing |
| Main technology types | Selexol, Rectisol, Purisol | MEA scrubbing, physical absorbers |
| Current technological maturity | Demo and early commercial scale | Widespread commercial availability |
| Primary limitations | High costs, integration complexity | Extensive energy usage for solvent regeneration |

**Table 3.1** Comparison of pre-combustion and post-combustion $CO_2$ capture approaches

### 3.3 Oxyfuel Combustion for $CO_2$ Capture

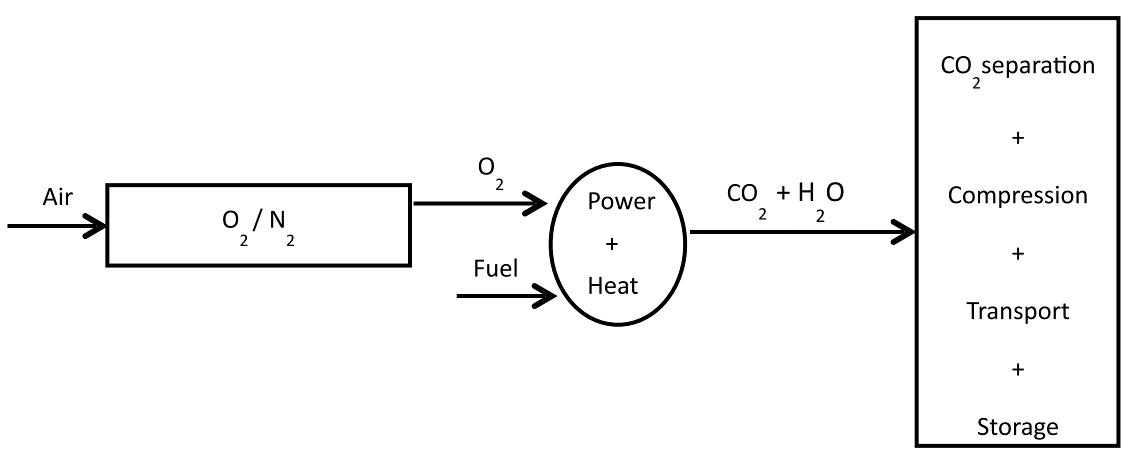

**Figure 3.3** Oxy-fuel combustion[1]

Oxyfuel combustion capture utilizes high-purity oxygen rather than air for the combustion of fuels to produce a flue gas stream consisting mainly of $CO_2$ and water vapor. After condensing out the water vapor, a relatively pure $CO_2$ stream is obtained that can be processed for storage and sequestration. This technique eliminates the need for an additional costly air separation unit as required for post-combustion capture. However, oxygen production consumes a significant amount of energy, increasing fuel requirements per unit of electricity generated. While technically feasible, oxyfuel combustion is more expensive than post-combustion capture using amine scrubbing. Oxyfuel systems have been demonstrated at the pilot scale, but more commercial availability is needed. Key technical barriers are developing optimal oxyfuel boiler designs, achieving proper flue gas conditioning, and integrating $CO_2$ purification systems.[1,2]

### 3.4 Emerging $CO_2$ Capture Concepts

In addition to conventional pre-combustion, post-combustion, and oxyfuel systems, several emerging concepts have the potential for more energy-efficient $CO_2$ capture. Microalgae cultivation can fix $CO_2$ into biomass via photosynthesis. However, significant challenges exist in scale-up, water use, and harvesting.[1] Enzyme-based systems can potentially absorb $CO_2$ at lower temperatures than current solvents.[7]Artificial leaf designs mimic natural photosynthesis, converting $CO_2$ and water to synthesis gas using solar energy.[1] $CO_2$ hydrates form ice-like cage structures to capture $CO_2$ at high pressures but are still early in development.[1,2]

While promising, these novel techniques face hurdles related to scalability, integration into existing facilities, and costs compared to incumbent systems before they are commercially viable. Extensive research is underway to improve and optimize emerging $CO_2$ capture concepts.

## 4. $CO_2$ Separation Technologies

After carbon dioxide has been captured from flue gas streams, it must be effectively separated and purified for transport, utilization, or storage. $CO_2$ separation is thus a critical process within carbon capture, utilization, and storage (CCUS) systems. Various separation techniques have been developed, from mature approaches like chemical absorption to emerging methods like membranes and adsorption. This section provides an overview of established and innovative $CO_2$ separation technologies, assesses their current advantages and limitations, and identifies research gaps for further advancement. Chemical absorption using amines such as monoethanolamine (MEA) is the most proven and widely used separation process, achieving high $CO_2$ purity. However, the high energy consumption for solvent regeneration remains a crucial challenge. Adsorption and membrane separation offer alternatives with the potential for lower energy usage, although real-world testing at scale is limited.[17] The solvents and adsorbents used in $CO_2$ capture processes can be degraded by impurities in the flue gases, reducing their effectiveness and increasing the cost of operation. Cryogenic separation is also possible but energy-intensive. Ongoing research aims to develop advanced solvents, sorbents, and membranes with improved selectivity, kinetics, and durability to minimize the energy penalties and costs of producing high-purity $CO_2$.[17] While progress has been made, additional pilot-scale testing and demonstrations are required to optimize separation systems for integration with diverse $CO_2$ capture sources.

### 4.1 Chemical Absorption

A variety of separation techniques exist to extract and purify $CO_2$ from flue gas streams after capture processes. Chemical absorption using amine-based solvent scrubbing is the most proven and widely applied approach.[2] Solvents such as monoethanolamine (MEA) reversibly bind $CO_2$ through exothermic reactions as the flue gas bubbles through the solvent solution.[5] The $CO_2$-rich solvent is then sent to a stripper, where heat is applied to reverse the absorption reaction and release a concentrated stream of $CO_2$ for downstream use. While effective at removing $CO_2$, amine scrubbing systems that employ solvents like MEA have substantial energy requirements for the stripping process to regenerate the solvent after absorption.[3] Research is ongoing into advanced amines, solvent blends, intercooling, and other process optimizations to reduce this energy penalty.[1] However, the low cost of amine solvents and proven high removal efficiencies at commercial scale favor chemical absorption.[2,]

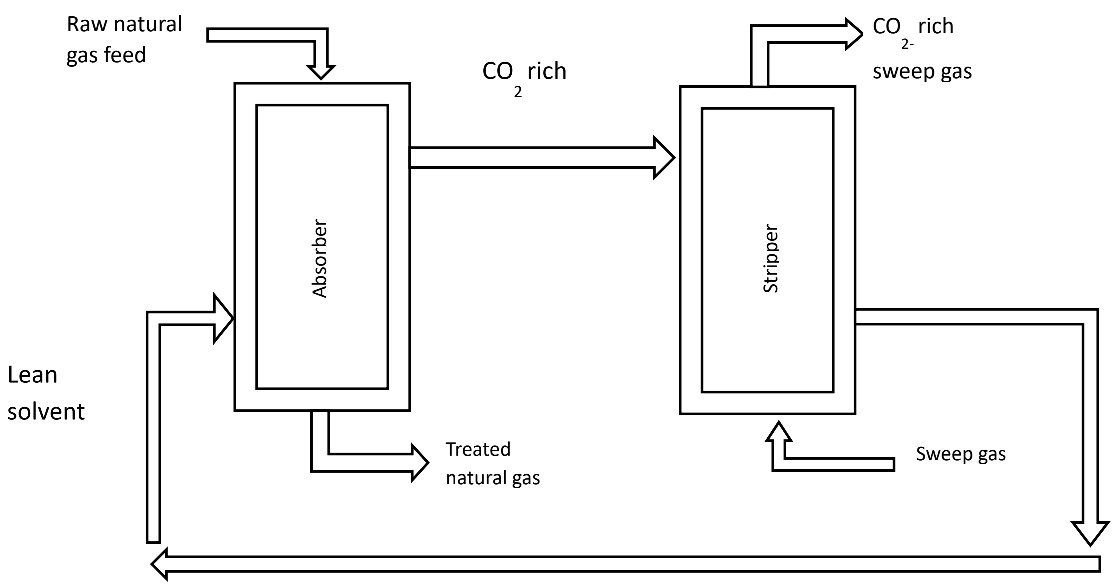


**Figure 4.1** Reactive absorption in closed loop[19]

### 4.2 Adsorption

Adsorption processes offer another separation approach that selectively uses porous solid media such as zeolites, activated carbons, and metal-organic frameworks to adsorb $CO_2$ at ambient temperatures. This eliminates the energy for heating during regeneration. Pressure or vacuum swing adsorption systems work by cycling the adsorbent material between adsorption under pressure and regeneration under vacuum to release the $CO_2$.[7] While adsorption can potentially lead to lower energy usage than heated stripping in absorption methods, the technology has only been demonstrated at a small pilot scale under natural flue gas conditions. Finding optimal stable adsorbent materials over repeated adsorption-regeneration cycles and integrating adsorption vessels into full-scale capture systems remains challenging.[2]

Emerging adsorbents like metal-organic frameworks (MOFs) and zeolitic imidazolate frameworks (ZIFs) offer ultrahigh surface areas, tunable pore sizes, and selective $CO_2$ binding sites.[7] Process intensification methods like rapid temperature swing adsorption (RTSA) are also being studied.[7] Table 4.1 highlights some key advantages and limitations of adsorption techniques.

| **Advantages**[2,8] | **Disadvantages**[2] |
|---|---|
| Ambient temperature operation, no heating | Limited large-scale demonstrations with flue gas |
| Rapid cycling between adsorption and regeneration | Sorbent poisoning from flue gas contaminants |
| Potential for lower energy usage vs absorption | Sorbent breakdown with cycling |
| Modular and scalable vessel design | High land footprint for full-scale systems |

**Table 4.1.** Adsorption advantages and disadvantages

#### 4.3 Membrane Separation

Membrane separation utilizes polymer materials that allow for selective permeation of $CO_2$ over other flue gas components due to differences in permeabilities.[1] This separation is driven by the membrane's pressure, temperature, or electrical potential gradients. Ceramic and metal membranes are also under development. Key advantages of membranes are the lack of heating requirements, modular and scalable construction, and smaller land footprint compared to absorption towers.[5] Challenges in membrane separation includes the low concentration of $CO_2$ in flue gas (~15%) and also the low partial pressure of $CO_2$ which results in low permeance.[1] Flue gas also consists of a number of impurities such as $SO_x$, $NO_x$, HCl, which results in low selectivity for $CO_2$.[1,5] Advanced membrane materials like poly(ethylene oxide) (PEO) complexes, porous graphene, and zeolite imidazolate frameworks (ZIFs) aim to improve selectivity and permeance.[5]

#### 4.4 Cryogenic Distillation

Cryogenic distillation for $CO_2$ separation from flue gas involves lowering the temperature to below -50°C to condense pure $CO_2$ from other gases based on differences in boiling points. This cryogenic cooling causes $CO_2$ to liquefy while lighter components like nitrogen and oxygen remain gaseous. The condensed $CO_2$ stream can then be vaporized to isolate it in a purified form.[2] However, sizeable external refrigeration loads provided by energy-intensive compression cooling cycles are required to achieve cryogenic temperatures. Moreover, expensive alloy or stainless steel equipment is frequently required due to low temperatures.[5] Additionally, freezing of water and $NO_x$ compounds present in flue gas can cause blockages.[2] While it is possible to obtain high-purity

$CO_2$ using this method, the complex, costly equipment and extremely high parasitic energy loads render cryogenic separation impractical for large-scale $CO_2$ capture processes.[5]
Research into innovative refrigeration techniques and process improvements is ongoing to increase its viability.

## 5. $CO_2$ Transport Methods

Transportation of captured $CO_2$ from emissions sources to utilization or storage locations is a critical link in the overall carbon capture, utilization, and storage (CCUS) chain. Various transport methods have been proposed and demonstrated for moving $CO_2$, each with advantages and limitations. Key considerations in selecting appropriate $CO_2$ transport options include the volume of $CO_2$ to be moved, the transport distance, geographic factors, infrastructure requirements, and relative costs.[8] This section reviews the current status and future outlook for the main $CO_2$ transport modalities - pipelines, shipping, rail, and trucks.

### 5.1. Pipelines

Pipelines are considered the workhorse option for onshore transport of large, steady volumes of $CO_2$. Captured $CO_2$ is first compressed into a dense supercritical state to maximize mass flow through the pipeline.[2] Compressor stations along the length of the pipeline keep the $CO_2$ pressurized. In some cases, existing pipeline networks built for enhanced oil recovery operations could be leveraged or expanded for CCS.[8] Still, new dedicated $CO_2$ pipelines would also likely need to be constructed with widespread CCS adoption. Managing impurities in the $CO_2$ stream and preventing internal pipeline corrosion are two technical design challenges.[1] Overall, pipelines are the most economical transport option for primary stationary $CO_2$ sources, producing volumes in the millions of tonnes per year.[34]

### 5.2. Shipping

For offshore storage sites or coastal capture facilities, $CO_2$ can be transported via seagoing tanker. After compression and liquefaction, the dense phase $CO_2$ is loaded into heavily insulated tanks aboard the specialized $CO_2$vessel.[1] Shipping provides more geographic flexibility than fixed pipelines, albeit with smaller potential capacities.[40] While minimal new port infrastructure is needed, significant energy is required for liquefaction. In general, shipping can accommodate capture sources unsuitable for pipeline transport and is a versatile choice for different storage reservoirs.[2]

### 5.3. Rail and Trucks

Transport of $CO_2$ via rail in pressurized cylinders loaded onto railcars or via tractor-trailer trucks allows flexibility for shorter distances or connecting capture facilities to pipelines. Existing rail and truck fleets could enable easy deployment, but capacities are limited to about 30 tonnes of $CO_2$ per shipment.[2] This likely restricts rail and truck transport to small pilot deployments of CCUS. Loading and unloading $CO_2$ cylinders also requires strict safety precautions.[8]

In summary, a network utilizing multiple transport modes will likely be required for widespread CCUS implementation, with pipelines serving major point sources, shipping providing geographic flexibility, and rail and trucks suited for small volumes over shorter distances.[29] Ongoing research aims to reduce the costs and energy requirements for compression, liquefaction, and transportation of anthropogenic $CO_2$.[25]

## 6. $CO_2$ Utilization Options

Captured carbon dioxide can be utilized in various industrial processes and commercial products rather than being directly stored. However, the feasibility, scalability, and ultimate impact on $CO_2$ emissions reduction of different utilization pathways remains to be determined. The primary methods for using $CO_2$ are reviewed in this section, along with the drawbacks and future prospects for each particular application. These methods include enhanced oil recovery, chemical synthesis, fuel synthesis, microalgal cultivation, and mineral carbonation. By utilizing captured $CO_2$, it can be seen that CCS alone is not lucrative but CCUS is.

### 6.1. Enhanced Oil Recovery

Enhanced oil recovery (EOR) using injected carbon dioxide is one pathway for potentially utilizing captured $CO_2$. Injecting compressed $CO_2$ into declining oil fields can mobilize additional oil through fluid viscosity reduction and oil swelling mechanisms.[4] While $CO_2$-based EOR provides economic value from incremental oil produced, most injected $CO_2$ remains underground, with only an estimated 20-60% of the injected $CO_2$ being recaptured along with oil and gas production.[9] This results in a portion of the injected $CO_2$ being permanently trapped in the reservoir through capillary, solution, and mineral trapping mechanisms. However, the overall climate change mitigation benefit is ambiguous since the oil produced is typically combusted, releasing $CO_2$ emissions.[4] While it offers economic incentives, the scale of $CO_2$ utilization for EOR is well below the levels required for substantial emissions reductions.[20]

### 6.2. Chemical Production

Captured carbon dioxide can be used as a feedstock in the chemical industry to produce various useful compounds. The conversion of $CO_2$ into chemicals provides an opportunity to consume $CO_2$ in an economically productive manner instead of emitting it. However, the scale of $CO_2$ utilization through chemical production pathways still needs to be improved. The maximum realistic technical potential for chemical manufacturing use of $CO_2$ is estimated at around 300 million metric tons per year globally.[4] Significant life cycle environmental impacts can also arise from the additional inputs like fossil fuels required for the chemical processes that utilize $CO_2$.[22] Major chemical production pathways using $CO_2$ include urea synthesis for fertilizers, methanol production, polymer and plastic manufacturing, and production of organic carbonates.[10] Key barriers include high costs compared to existing production routes from fossil fuels, the intermittent nature of $CO_2$ supply from capture sites, and overall limits on market size for potential products.[25] While $CO_2$ chemical conversion offers opportunities, it does not appear capable of utilizing $CO_2$ at the multi-gigatonne scales necessary for substantial climate change mitigation without combination with permanent carbon storage.[4,21]

### 6.3. Fuels Synthesis

Captured $CO_2$ can be used as a raw material for synthetic fuel production via catalytic and electrochemical processes. Catalysis plays a crucial role in the utilization of $CO_2$ for fuel synthesis by facilitating the conversion of $CO_2$ into valuable fuels and chemicals. Without catalysts, these reactions would be too slow and inefficient to be practical. Catalysts achieve this by lowering the activation energy of the reactions, making them occur more readily and at lower temperatures.[34] The specific type of catalyst used in a $CO_2$ utilization process depends on the specific reaction being carried out. For example, nickel catalysts are often used for the hydrogenation of $CO_2$ to produce methane, while copper catalysts are often used for the reverse water-gas shift reaction to produce CO from $CO_2$ and $H_2$.[36] The use of catalysts in $CO_2$ utilization has the potential to revolutionize the way we produce fuels and chemicals. By converting $CO_2$ into valuable products, reliance on fossil fuels can be reduced and effects of the climate change can be mitigated.[23] However, significant investments in new infrastructure would be required. Estimates suggest fuel synthesis could utilize less than 200 million tonnes of $CO_2$ per year due to economic constraints.[4] Significant energy inputs are also often needed.[4]

#### 6.4. Microalgal Cultivation

Microalgae are receiving growing attention for their ability to fix carbon dioxide into biomass that can be used for biofuels, feeds for both humans and animals, foods, and other products. Microalgae naturally utilize $CO_2$ for growth through photosynthesis and can achieve higher productivity than conventional terrestrial crops.[4] Cultivating microalgae on captured $CO_2$ provides a biomass-based pathway for potentially recycling carbon emissions into value-added products.[3] However, significant challenges exist in developing and operating large-scale microalgae cultivation systems matched to $CO_2$ sources.[3] Constraints include requirements for sunlight, water, nutrients, land, and costs associated with bioreactor construction, operation, and biomass harvesting.[4] The maximum potential for utilizing $CO_2$ through microalgal systems is likely less than 200 million metric tons per year due to geographical, resource, and economic limitations.[4,19] While research continues increasing productivity and process efficiencies, microalgae cultivation cannot realistically utilize $CO_2$ emissions at the scale necessary for climate change mitigation based on the total availability of land, water, and nutrients.[26,24]

#### 6.5. Mineral Carbonation

$CO_2$ reacts naturally with metal oxides in minerals to form stable carbonates. Enhancing this geological process via mining and mineral processing could provide gigatonne $CO_2$ storage capacity but faces immense costs and energy requirements.[3]

While $CO_2$ can be utilized in various methods, applications are limited in scale and can only achieve the emissions reductions required for climate targets by pairing with carbon storage.[4] None of the utilization options appear to be able to consume the billions of tonnes of $CO_2$ requiring capture each year.[19]

#### 6.6. Integrated Carbon Capture and Utilization (ICCU)

Integrated $CO_2$ capture and utilization (ICCU) is an emerging technology where unlike conventional CCUS, which involves capturing $CO_2$, transporting it to a storage site, and then utilizing it for various purposes, these steps are combined into a single integrated system. ICCU systems comprise of two steps. The first step is $CO_2$ capture in which $CO_2$ is captured from flue gases or other sources using various methods, such as absorption, adsorption, or membrane separation. In second step the captured $CO_2$ is then directly converted into valuable products using catalytic or chemical processes. The specific products produced depend on the type of $CO_2$ conversion technology employed.

ICCU achieves $CO_2$ adsorption, separation and conversion using dual-function materials (DFMs), which consist of $CO_2$ adsorbents and catalysts. First, DFMs can capture $CO_2$ from flue gas (~15 vol% $CO_2$) to effectively reduce carbon emissions. When the carbon capture process is completed, the feed gas is switched to a reducing agent for the conversion of the adsorbed $CO_2$ accomplished with the regeneration of the adsorbents.[16] The reduction of $CO_2$ in ICCU is carried out under reducing agent-rich conditions, further avoiding the purification of products by significantly improving the conversion of $CO_2$.The ICCU process shortens the path of $CO_2$ utilization such as $CO_2$ transportation and storage, and further negates the need for purification of products owing to the high conversion of $CO_2$. ICCU can reduce energy consumption, improve economic viability, and enhance environmental benefits. As an emerging integrated process, the improvement of ICCU performance is crucial for future applications.[16]

## 7. $CO_2$ Storage

Permanent geologic storage of $CO_2$ is critical for climate change mitigation, with storage capacities far exceeding expected emissions. The primary options for $CO_2$ storage include saline aquifers, depleted oil and gas reservoirs, deep ocean sequestration, and geologic mineralization.[6] Each pathway offers advantages and poses technical and economic challenges that must be managed for safe, adequate long-term $CO_2$ storage.

Deep saline aquifers provide immense potential capacity for geologic storage of anthropogenic carbon dioxide, with estimated global capacity ranging from 1000 to 10,000 $GtCO_2$.[2] Saline formations are sedimentary rocks saturated with formation water unfit for human consumption or agriculture located in subsurface layers thousands of meters below the surface. Injecting captured $CO_2$ into these deep formations enables secure long-term sequestration as the buoyant $CO_2$ rises until trapped by impermeable caprock.[26,25] Saline aquifers have been utilized for subsurface gas storage operations for decades. Pilot projects injecting $CO_2$ into saline aquifers have demonstrated stable plume behavior and verified models of the complex fluid dynamics involved. Ongoing research aims to properly site, model, and monitor commercial-scale $CO_2$ storage in saline formations.[2,6]

Mature oil and gas reservoirs effectively sealed by caprock provide excellent potential sites to store injected anthropogenic carbon dioxide. Depleted hydrocarbon reservoirs have a proven capacity to trap and contain gases underground for geologic timescales.[6] Used in enhanced oil recovery, $CO_2$ injection offers economic incentives that can offset storage costs.[2] Estimated $CO_2$ storage capacities in depleted oil and gas reservoirs range up to hundreds of $GtCO_2$ globally. However, continuous monitoring is required to detect potential leakage issues.[6,1]

Injecting captured $CO_2$ into the deep ocean water column or sediments could offer substantial potential storage capacity. However, concerns regarding potential impacts on marine ecosystems may limit deployment.[2] Large-scale deep ocean $CO_2$ injection testing has yet to occur, and developing regulations poses challenges.[12] While promising in principle, many unknowns remain around deep ocean sequestration.

Injecting carbon dioxide into reactive rock formations can accelerate natural mineral carbonation processes that lock $CO_2$ into stable mineral forms. This provides a permanent storage solution. Estimates for $CO_2$ storage capacity through enhanced mineralization range widely from tens to hundreds of $GtCO_2$.[13,28] However, energy is required for mineral processing, and uncertainties around rates and risks exist. Ongoing field demonstrations aim to improve assessments and knowledge of in situ mineralization processes.[27]

## 8. Economic and Policy Consideration

While carbon capture, utilization, and storage (CCUS) technologies are being established, economic and policy measures will be instrumental in allowing widespread commercial deployment. Reducing energy penalties in capture and compression is the key to lowering costs.[7] Tax credits, carbon pricing programs, mandates, and other mechanisms can help incentivize CCUS. Many policies focus on electricity, but industrial CCUS also needs support.[33,38]

CCUS applications do not all have the same cost. Looking specifically at carbon capture, the cost can vary greatly by $CO_2$ source, from a range of USD 15-25/t $CO_2$ for industrial processes producing “pure” or highly concentrated $CO_2$ streams (such as ethanol production or natural gas processing) to USD

40-120/t $CO_2$ for processes with "dilute" gas streams, such as cement production and power generation. Capturing $CO_2$ directly from the air is currently the most expensive approach, but could nonetheless play a unique role in carbon removal.[32,36,37] Some $CO_2$ capture technologies are commercially available now, while others are still in development, and this further contributes to the large range in costs.[31]

The cost of transport and storage can also vary greatly on a case-by-case basis, depending mainly on $CO_2$ volumes, transport distances and storage conditions. In the United States, for example, the cost of onshore pipeline transport is in the range of USD 2-14/t $CO_2$, while the cost of onshore storage shows an even wider spread.[22] However, more than half of onshore storage capacity is estimated to be available below USD 10/t $CO_2$.[27] In some cases, storage costs can even be negative if the $CO_2$ is injected into (and permanently stored in) oilfields to enhance production and thus generate more revenue from oil sales.[39]

International collaboration is also essential for the further spread of CCUS technologies. Clear regulations around project permits, $CO_2$ storage site management, monitoring requirements, and liability are crucial for investment. Consistency across regions is also needed.[35] There is considerable potential to reduce costs along the CCUS value chain, particularly as many applications are still in the early stages of commercialization.[34] CCUS should become cheaper as the market grows, the technology develops, finance costs fall, economies of scale are reached, and experience of building and operating CCUS facilities accumulates. This pattern has already been observed for renewable energy technologies over recent decades. Cost reductions have already been achieved at large-scale CCUS projects. For example, the cost of $CO_2$ capture in the power sector has come down by 35% through its evolution from the first to the second large-scale CCUS facility, and this trend is set to continue as the market expands.[34]

Table 8.1 highlights the estimated costs for different CCUS components.[7] Further R&D can improve capture efficiency, reduce energy penalties, lower transport costs, advance utilization options, and ensure safe geologic storage.[1] Emerging techniques like membranes, mineralization, and algae cultivation require continued piloting and assessment.[14] Table 8.2 highlights the projected cost, which can be reduced for different CCUS components.[1]

| Process | Estimated Cost Range[8] |
| --- | --- |
| $CO_2$ capture | \$50-100/t$CO_2$ |
| $CO_2$ transport | \$3-15/t$CO_2$ |
| $CO_2$ storage | \$0.5-10/t$CO_2$ |
| Total w/o utilization | \$53-125/t$CO_2$ |

**Table 8.1** Estimated costs of CCUS components

| Process | Potential Cost Reduction[1] |
| --- | --- |
| $CO_2$ capture | 10-30% |

| | |
|---|---|
| $CO_2$ transport | 5-15% |
| $CO_2$ utilization/storage | 10-20% |

**Table 8.2** Projected cost reduction for CCUS components

## 9. Future Outlook and Priorities

Even though carbon capture, utilization, and storage (CCUS) have shown progress, more advancements and deployment efforts are required for CCUS to reach its full potential in reducing emissions. Key priorities include advancing technologies, accelerating commercial adoption, and gaining public acceptance.[2,19] Incentives like tax credits for $CO_2$ utilization/storage, emission caps, carbon pricing, and low-interest loans can help drive commercial CCUS projects. Deployment is also made more accessible by simplifying permits and making legal frameworks more understandable.[1,40] Gaining societal acceptance can be facilitated by proactive stakeholder engagement and education on CCUS technology, safety, and sustainability. It's essential to communicate lifecycle analyses and concrete benefits to the masses.[15,32]

## 10. Results

Despite the encouraging progress, the persistent challenge of cost reduction remains. While the cost of CCUS technologies is decreasing, they remain more expensive than conventional energy production methods. Overcoming this economic barrier is crucial to making CCUS a more competitive and attractive option for industries seeking to reduce their carbon footprint. The widespread deployment of these systems, coupled with continued technological improvements and supportive policies, will be instrumental in reducing greenhouse gas emissions and transitioning to a low-carbon future.

## 11. Discussion

The findings of the review suggest that CCUS technologies have the potential to play a significant role in reducing greenhouse gas emissions. However, further development and demonstration of these technologies are needed to reduce costs, improve performance, and validate their effectiveness and reliability in real-world applications. The study also highlights the need for policies to support the deployment of CCUS technologies. These policies include carbon pricing, investment subsidies, and tax breaks.

## 12. Conclusions

Carbon capture, utilization and storage (CCUS) technologies are critical for putting energy systems around the world on a sustainable path. CCUS technologies can be retrofitted to power and industrial plants that may otherwise emit 8 billion tonnes of $CO_2$ in 2050 – around one-quarter of today's annual energy-sector emissions.[8] CCUS can tackle emissions in sectors with limited other options, such as cement, steel and chemicals manufacturing, and in the production of synthetic fuels for long-distance transport. CCUS enables the production of low-carbon hydrogen from fossil fuels, a least-cost option in several regions around the world. CCUS can remove $CO_2$ from the atmosphere by combining it with bioenergy or direct air capture to balance emissions that are unavoidable or technically difficult to avoid.

The most common way to capture carbon is pre combustion capture as it captures $CO_2$ before the fuel is burned and it is highly efficient as compared to other methods discussed but the cost and the complex nature of this method is the biggest disadvantage. Similarly, captured carbon can be used in greenhouses to promote plant growth, improving crop yields and reducing the needs for artificial fertilizers. However, every method discussed carries a potential for both gain and loss. Limiting the availability of CCUS would considerably increase the cost and complexity of the energy transition by increasing reliance on technologies that are currently more expensive and at earlier stages of development.

The next decade will be critical to the prospects for CCUS and for putting the global energy system on a path to net-zero emissions. A significant scaling-up of CCUS is needed to provide the momentum for further technology development and cost reductions, and to foster progress across a broader range of applications in the long term. The purpose of this review was to compile information about the current state of CCUS and the most promising areas for future advancement, providing policymakers, researchers, industry, and other stakeholders with a framework for guiding CCUS toward widespread global adoption. Meeting ambitious climate goals will require immediate, aggressive efforts across all mitigation options – and as highlighted here, carbon capture, utilization, and storage must be part of comprehensive climate change solutions.

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## 14. References

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