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Characteristics and Challenges of Carbon Capture and Storage Technologies

Xianglong Huang[1,a,*]

[1]Earth Science Department, University College London, London, WC1E 6BT, UK
a. zczquaf@ucl.ac.uk
**corresponding author*

Abstract: Climate change is a pressing global issue, leading to the establishment of various carbon reduction goals, and thus carbon capture and storage (CCS) technology has attracted considerable attention. This article provides an overview of the primary carbon capture and storage technologies, explores their technical principles along with their pros and cons, and examines the challenges they encounter. There are three ways to capture carbon: post-combustion, pre-combustion, and oxy-combustion. Post-combustion capture includes adsorption, absorption and membrane separation. Adsorption can be further categorized into four specific technologies: Temperature Swing Adsorption (TSA), Pressure swing adsorption (PSA), Vacuum swing adsorption (VSA), and Electric swing adsorption (ESA). Absorption has physical and chemical types. Membrane separation is to filter the gas to CO2. Pre-combustion capture is to use physical solvents to separate the gas. Oxy-combustion uses pure oxygen to obtain CO2. There are three ways to store carbon, geo-sequestration, marine storage and mineralization storage. Geo-sequestration is to bury CO2 in a suitable state in the rock layer below the surface. Marine storage is to bury CO2 in various places in the sea in a classified manner. Mineralization storage refers to the use of solid waste rich in calcium and magnesium to mineralize CO2 and produce chemical products. There are three main challenges facing CCS technology: economically, the cost is too high with low benefits. The technology is not mature enough and will consume too much energy. Environmentally, there is a potential for ecological deterioration.

Keywords: CCS, CO_2, Carbon Storage, Carbon Capture.

1. Introduction

Climate change, predominantly fueled by greenhouse gas emissions resulting from human activities, represents one of the most urgent environmental challenges of our era. Among these gases, CO_2 plays a significant role. Therefore, reducing atmospheric CO_2 levels to mitigate climate change impacts has become a pressing priority. The Paris Agreement aims to limit global temperature rise to within 2 degrees Celsius, prompting 175 countries to commit to substantial carbon emission reductions. This has led to increased focus on Carbon Capture and Storage (CCS) technology, a promising solution for reducing emissions and promoting a low-carbon economy. CCS involves capturing CO_2 using post-combustion, pre-combustion, and oxy-combustion techniques, and storing it via geo-sequestration, marine storage, or mineralization. This paper reviews CCS technologies, their principles, advantages, and disadvantages, and the challenges they encounter.

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2. Technical Background of CCS

2.1. Carbon Capture

2.1.1. Post-Combustion Capture

Post-combustion capture involves capturing CO_2 from the exhaust gas generated during combustion using an appropriate solvent (Figure 1) [1]. This carbon capture process can be divided into three main categories based on the underlying principles: adsorption, absorption, and membrane separation [2].

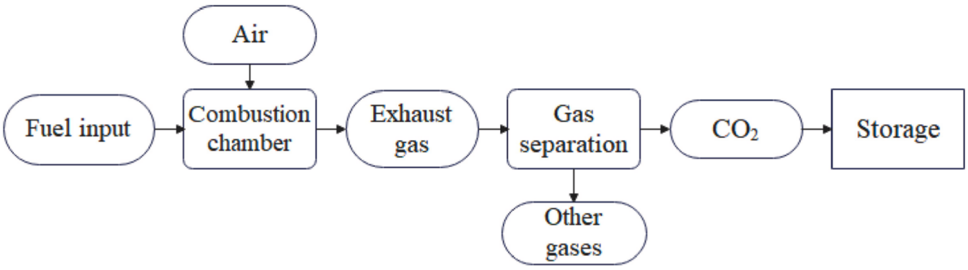

Figure 1: Post-combustion carbon capture [3].

(1) Adsorption

1) Temperature Swing Adsorption (TSA)

TSA is used to complete the CO_2 adsorption and desorption cycle by changing the operating temperature. In the TSA process, CO_2 adsorption is carried out at low temperature (maximum 60°C, minimum 40°C), but desorption requires higher temperature (minimum 120°C, maximum 160°C), which means that the adsorption tower is first set at 60°C to capture CO_2, then heated to 120°C with hot steam to release them, and finally heated to 160°C to remove possible impurities [2]. TSA applications can maximize the use of screening capacity because high temperature regeneration is most effective in removing adsorbed contaminants. In most cases, TSA is used to remove the contaminants CO_2 and H2O.

2) Pressure Swing Adsorption (PSA)

PSA is a method used to separate specific gases from a mixture (typically air) under pressure. The process works by relying on the differences in the molecular properties of CO_2 and nitrogen and their affinity for a solid adsorbent. At higher pressures, CO_2 is selectively adsorbed by the adsorbent bed, while nitrogen is not [2].

The following outlines various hydrogen sources, including their pressure, hydrogen content, and impurities:

Steam reformer syngas: 20–30 bar, 70-80 mol% hydrogen, with CO_2 as the main impurity, plus methane, carbon monoxide, and nitrogen.

Refinery off-gas: 8-22 bar, 65-85 mol% hydrogen, primarily methane, with ethane, propane, and butane.

Ethylene off-gas: 25-35 bar, 70-90 mol% hydrogen, mainly methane, along with carbon monoxide, ethylene, and ethane.

Methanol off-gas: 50-65 bar, 60-70 mol% hydrogen, with methane as the main impurity, plus carbon monoxide and nitrogen.

Coke oven gas: 5-15 bar, 55-60 mol% hydrogen, predominantly methane, with nitrogen, carbon monoxide, and CO_2.

Coal gasifier syngas: 30-50 bar, 85-95 mol% hydrogen, with CO_2 as the main impurity, and includes carbon monoxide, nitrogen, and argon.

The PSA process can be applied to other impurities besides CO_2, including but not limited to carbon oxides, alkanes, and olefins. Most feed streams are at pressures of 10-40 bar, but there are some outliers with pressures as low as 5 bar or as high as 65 bar [4].

3) Vacuum swing adsorption (VSA)

VSA separates specific gases (such as CO_2) from a gas mixture at near-ambient pressure, followed by transitioning to a vacuum to regenerate the adsorbent material. The VSA cycle comprises an adsorption step, a co-current blowdown step, a counter-current blowdown step, and a pressurization step [5]. This technology recovers CO_2 from power plant flue gases when it is in operation because the flue gas pressure is slightly above atmospheric pressure. Prior to CO_2 adsorption, the flue gas must be pretreated to remove moisture and particulate matter and sulfur species, as all of these contaminants can damage the adsorbent through irreversible adsorption or pore clogging [6].

VSA differs from the PSA technology mentioned above in that it operates at near-ambient temperature and pressure. Many factors affect the operation of a VSA system, such as feed gas temperature and CO_2 content, pressure, adsorbent and other gas impurities. In addition, Cong Chao showed that when the VSA feed temperature was 40°C and a moderate vacuum was used, the CO_2 recovery rate of the VSA process exceeded 70%, the CO_2 purity exceeded 90%, and the electricity cost was low [2].

4) Electric swing adsorption (ESA)

ESA technology utilizes the Joule effect, where an electric current passing through a conductor generates heat to raise the temperature of the adsorbent and regenerate it. This method employs an adsorbent to separate heavier substances (more retained) from lighter ones (less retained) within a mixture. To regenerate the adsorbent bed, an electric current is applied, increasing the temperature due to the Joule effect. Once the process is complete, the temperature is lowered back to the feed level, and the bed is ready for a new cycle [7].

ESA offers several advantages over other technologies, including faster heating rates, reduced heat requirements, improved desorption kinetics and dynamics, and the ability to independently regulate gas and heat flow rates. However, it also has limitations, particularly in handling large gas volumes efficiently. In contrast, TSA technology is more suitable for managing larger gas volumes [8].

(2) Absorption

Physical absorption method refers to Henry's law. Pressure and temperature affect the solubility of CO_2 in the absorbent. It is currently used in industries with high CO_2 emission concentrations. The chemical absorption method causes CO_2 to react chemically with the absorbent to generate a salt with an unstable structure, which is then heated to release CO_2. However, since the regeneration of the absorbent consumes a lot of heat energy, the absorbent loss is large, the operating cost is high, and the equipment investment is large, it is mainly used in industries with low CO_2 emission concentrations such as natural gas processing [9].

(3) Membrane Separation

This technology allows the membrane to form a semipermeable barrier by various means, such as dissolving, adsorbing and classifying some of the particles that pass through it [2]. Because different gases have different permeabilities to the membrane, they will be selectively separated from a group of mixed gases one by one. The advantages of this method are high efficiency, simplicity, energy saving, and reduced loss of organic solvents. Nowadays, the morphology of membranes can be specifically divided into liquid and solid states [10]. Its performance mainly considers its permeability and selectivity, which themselves mainly depend on the properties of the membrane and the applied temperature, pressure and other conditions.

In the capture of CO_2, since it does not involve regeneration or chemicals, the capital cost required is not large. However, Cong et al. stated that higher initial pressure is required for membrane separation to be efficient. If CO_2 is too low, the effect of membrane separation technology will not be very good. This is the main challenge of this technology in CO_2 separation [2].

2.1.2. Pre-Combustion Capture

Pre-combustion capture entails removing CO_2 from fossil fuels prior to completing the combustion process. Its chemical principle is to allow air and water vapor to gasify and reform fossil fuels before burning, and finally react to produce CO_2 (carbon monoxide and oxygen after steam reforming) and hydrogen (Figure 2). This technology has the characteristics of low energy consumption and extremely high separation efficiency, and can capture most of the CO_2 in the fuel. The two gases are then separated by gas separation methods, and the hydrogen can be used as fuel, while the CO_2 will be captured [3].

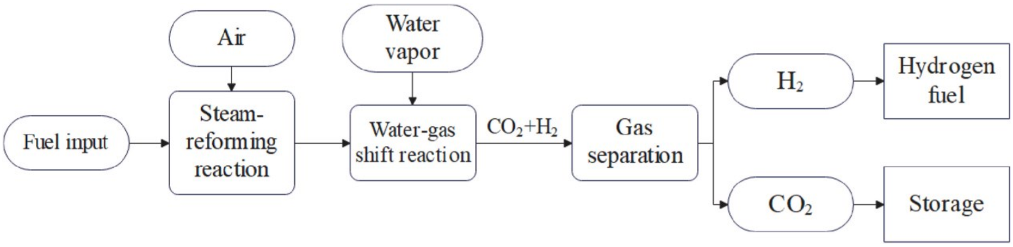

Figure 2: Pre-combustion carbon capture [3].

The key point in this process is to separate CO_2 and hydrogen. The most commercially advanced technology currently uses physical solvents to separate the two gases. The following presents various technology areas, detailing currently developed technologies and examples of technologies under development:

Absorption-based separation: Current technologies include physical solvents like Selexol and Fluor processes, as well as chemical solvents. Developments focus on novel solvents and improved process and equipment design.

Adsorption-based separation: Technologies under development include the sorption-enhanced water-gas shift (SEWGS) process and elevated temperature pressure swing adsorption.

Chemical looping systems: Technologies in progress include chemical looping combustion or reforming.

Membrane separation: Current developments involve metal and ceramic membrane WGS reactors and ion transport membranes.

Cryogenic separation: Existing technology includes CO_2 liquefaction, with ongoing development in hybrid cryogenic and membrane processes.

Compared with post-combustion capture, the concentration and pressure of CO_2 captured before combustion are higher, so smaller equipment with smaller footprint is required. However, this technology currently has limitations, and cost is one factor. Hua said that this technology would not be applicable in shipping, for example, as ships would need to add reactor tanks and modify hydrogen fuel engines [3].

2.1.3. Oxy-combustion

Oxy-combustion capture is achieved by first stripping oxygen from the air to fully burn fossil fuels, reacting to produce CO_2 and water vapor. The two are then separated by condensation technology, and the CO_2 is captured (Figure 3) [3].

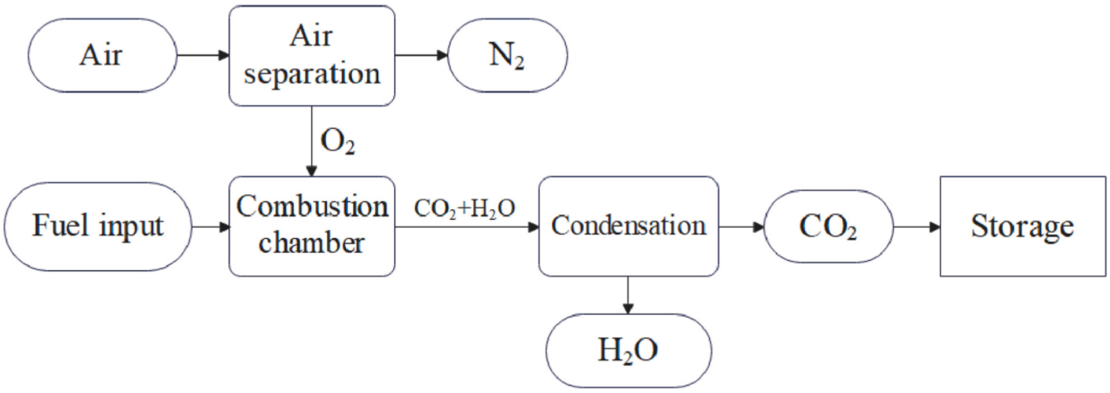

Figure 3: Oxy-combustion carbon capture [3].

It is worth noting that this technology involves burning fossil fuels in a pure oxygen environment, resulting in a high concentration of CO_2 with minimal impurities [3]. Therefore, the advantage of this technology is that no nitrogen is involved in the reaction, which reduces the use of a large number of capture equipment. However, this technology currently also has limitations. For example, the boiler part of the process needs to be redesigned to be suitable for working in a pure oxygen state. In addition, purifying the gas to a pure oxygen state also requires a lot of capital costs and energy consumption, which is also an issue that needs to be considered at present.

2.2. Carbon Storage

Carbon storage technologies currently include geo-sequestration, marine storage and mineralization storage [9].

2.2.1. Geo-sequestration

Traditional geo-sequestration involves the storage of CO_2 in suitable underground geological setting, such as coal seams, saline aquifers, and depleted oil and gas fields [9]. Since the 1970s, to improve the efficiency of oil extraction, people have begun to transport CO_2 underground [11]. Table 1 shows us the current CO_2 storage projects as of 2020.

Table 1: Global CO2 sequestration projects for climate change mitigation [11].

Project Name	The source of CO_2	Implementation time	Rate of CO_2 Injection	Achievements, Discoveries and Annotations
CO_2 Sequestration in Sedimentary Formations				
Sleipner	Natural gas processing	Starting from 1996	1 (Mt/yr)	First project to inject supercritical CO_2 into saline aquifers for long-term storage
In Salah	Natural gas processing	Starting from 2004, a total of 6 years	0.7 (Mt/yr)	Significant increase in reservoir pressure; geomechanical deformation without expected

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Table 1: (continued).

Snohvit	Natural gas processing	Starting from 2008	1 (Mt/yr)	The amount of CO_2 injected is rapidly decreasing. The solution is to inject it at different intervals.
Decatur	Chemical production	It started in 2011 and ended in 2014. After a three-year hiatus, it was implemented again in 2017	0.3, 1 (Mt/yr)	
Quest	Power generation	Starting from 2015	1.2 (Mt/yr)	
Gorgon	Natural gas processing	Under construction	3.4-4 (Mt/yr)	
CO_2 Sequestration in Basalt Formations				
CarbFix	Geothermal power generation, Direct air capture	From 2012 to 2016, from 2014 till now	200 (Mt/yr), 6,500 (Mt/yr)	Ending reason: upscaling of the project; Alternated injections of CO_2 and water to ensure complete dissolution at depth
Wallula	Geothermal power generation	Starting from 2009, a total of 4 years	977 (Mt/yr)	Injection of supercritical CO_2

Table 2 also shows us the status of CO_2 storage technology. Among these technologies, CO_2-EOR technology has been used and developed for more than ten years. It is the only effective method that can reach commercial level and can consider the storage of CO_2 and ensure economic benefits at the same time. Under normal circumstances, during CO_2 enhanced oil recovery and storage, the possibility of large-scale CO_2 leakage is very small, and it will not have a negative impact on the oil field and the surrounding environment [9]. Overall, this type of technology is highly feasible because it is safe and has little impact on the surface ecological environment.

Table 2: Basic information on CO2 geological storage and utilization technology [9].

Technology Name	Applicable Geological Bodies	Purpose	Efficiency and Evaluation
CO_2-Enhanced Oil Recovery	Depleted oil reservoirs	Improved Oil Recovery	It can increase crude oil recovery by at least 7% and extend the production life of oil wells by at least 15 years.
CO_2-Enhanced Coalbed Methane	Deep unminable coal seams	Improved coal seam gas extraction	It can store up to 12Gt, but has a very low CO_2 injection capacity and requires the reaction of CO_2 with the coal matrix.

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Table 2: (continued).

CO_2-Enhanced Gas Recovery	Depleted natural gas reservoirs	Improved natural gas recovery	The upper limit of storage capacity is 34.5Gt, but various mechanical principles of CO_2 gas fields still need further scientific research to solve.
CO_2 enhanced shale gas production technology	Shale	Improving shale gas recovery	Supercritical CO_2 used as fracturing fluid has strong adsorption, good fluidity, and is water- and slag-free.
CO_2-Enhanced Geothermal Systems (CO_2-EGS)	Geothermal system	Exploiting geothermal resources	There will be no errors in the dissolution and precipitation of minerals, and low energy consumption, but issues such as the role of CO_2 in geochemical processes are still unclear and require further scientific research to resolve.
CO_2 In-Situ Leaching Technology for Uranium Ore	Uranium	Uranium mining	The process has few process steps and will not cause a great impact on the environment, making it suitable for large-scale popularization in industry.
CO_2-Enhanced Water Recovery (CO_2-EWR)	Deep salt water	High value-added liquid mineral resources or mining of deep-water resources	It can store up to 144Gt of CO_2, while also reducing the pressure on the formation and the damage to water resources.

2.2.2. Marine storage

The ocean is the world's largest CO_2 storage reservoir. There are four forms of ocean CO_2 storage: one is to directly inject compressed CO_2 gas into the sea below 1500m and store it in gaseous, liquid or solid form under the ocean water column, among which CO_2 stored in solid form has the highest efficiency; the second is to use thick seabed sediments as a carrier, inject CO_2 into it, and store it under the pore water of the sediment layer; the third is to use CO_2 replacement to strengthen the exploitation of seabed natural gas hydrates; the fourth is to use the marine ecosystem to digest and store CO_2 [9].

From a long-term perspective, some studies believe that due to the influence of ocean currents, liquid CO_2 injected into the deep sea will cause seawater acidification and endanger the balance of the marine ecosystem. Research evidence from Radford et al. shows that increased CO_2 concentrations can affect the sensory systems of fish from temperate and tropical zones, such as fish hearing.

2.2.3. Mineralization storage

This technology mainly refers to the process of mimicking the CO_2 mineral absorption process in nature, using alkaline oxides in natural silicate ores or solid waste, such as CaO and MgO, to chemically absorb CO_2 and convert it into stable inorganic carbonates. CO_2 mineralization utilization refers to the use of solid waste rich in calcium and magnesium (such as steelmaking waste, cement kiln dust, fly ash, phosphogypsum, etc.) to demineralize CO_2 and produce chemical products. While

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achieving CO_2 emission reduction, it also obtains inorganic chemical products with certain value, improves the economic efficiency of CO_2 and solid waste resource utilization, and is a very promising large-scale fixed CO_2 utilization route [9].

3. Challenges of CCS Technology

Currently, CCS technology remains in the early stages of research, development, and demonstration, encountering numerous challenges in economic, technological, and environmental aspects. Significant obstacles and challenges still need to be addressed before it can achieve large-scale deployment.

3.1. Economics

The current important achievement of CCS technology is to reduce and remove carbon emissions. First, investing in CCS projects will require a lot of money, sometimes tens of millions or even hundreds of millions of dollars; second, carbon capture equipment will require additional operating and maintenance costs, and each ton of CO_2 will increase the amount by at least 140 yuan and at most 600 yuan; finally, for carbon sequestration, a higher price is required to capture CO_2, such as the price of purchasing CO_2 for CO_2-EOR is about 650 yuan/ton, which is not cost-effective for oil production companies.

3.2. Technology

CCS technology is a sophisticated technology that combines capture and storage technologies, and requires orderly and logical development of each link. First, the implementation of CCS capture will consume additional energy. In terms of the current global development capacity of this technology, the primary energy consumption will reach at least 110% to 120% of the previous energy consumption or even more, which is less efficient than before. Secondly, due to the chemical inertness and thermal stability of CO_2, a significant amount of energy is required to effectively convert and utilize it, which restricts the potential for resource utilization of CO_2. Therefore, it is necessary to find new catalysts to complete the new system. Third, in terms of geology, there are risks and uncertainties in both exploration and utilization. Due to the limitations of CO_2 geological storage and exploration technology, the information support is insufficient, and people cannot accurately assess the structure of the stratum, the storage capacity and potential risks. This leads to the possibility of companies doing business at a loss. Finally, under the current carbon neutrality goal, this technology needs to complete the task of reducing CO_2 emissions by at least 17.5 billion tons. However, there is a lack of suitable projects at present, so it is necessary to vigorously develop, deploy and promote CCS technology with obvious economic benefits.

3.3. Environment

Due to the chemical bond formation of CO_2, if there is an error in any link of CCS technology, such as leakage or wrong sequence of steps, it will affect our ecological environment. Under the current global technological level, the capture and transportation links will not have much impact on the environment. The main risk comes from how to use and store CO_2. From the perspective of geological time, due to geological movements such as earthquakes that are difficult to predict and control and the problem that CO_2 will corrode the strata, CO_2 is easy to spread to the ground, forming a greenhouse effect with a greater impact, causing a series problems and posing a danger to the health of organisms. This will also reduce people's recognition of CCS.

Given the characteristics of CCS itself, there are still some difficulties, such as difficulty in obtaining geological data, difficulty in quantitative evaluation, and difficulty in obtaining critical quantity standards for hazardous substances. Therefore, it is necessary to consider the entire process and stages of environmental monitoring and risk prevention and control of CCS projects and formulate effective plans.

4. Conclusion

This paper summarizes the current status of technology development and challenges in each link of carbon capture and storage.

Carbon capture technology primarily comprises post-combustion and pre-combustion capture methods, and oxy-combustion methods. Post-combustion capture includes adsorption, absorption and membrane separation. Adsorption includes TSA, PSA, VSA, ESA. It can be specifically categorized into chemical methods and physical methods (based on Henry's law). Membrane separation uses the different permeabilities of air. When the mixed gas passes through the membrane, it will be filtered and classified. Pre-combustion carbon capture is the process of gas separation using physical solvents. The working principle of oxy-combustion is to first strip oxygen from the air to fully burn fossil fuels, and then react to obtain CO_2 and water vapor, and then separate the two through condensation technology and capture the stripped CO_2. Carbon storage technologies mainly include Geo-sequestration, marine storage and mineralized storage. Geo-sequestration is the storage of CO_2 in unmineable coal seams, deep saline water layers and depleted oil and gas reservoirs. Marine storage has four types of storage methods. The first method involves compressing CO_2 and storing it as a gas, liquid, or solid beneath the ocean water column; the second is to inject CO_2 under the pore water of the sedimentary layer; the third is to replace it with seabed natural gas hydrates; and the fourth is to use the marine ecosystem for absorption and storage. Mineralized storage refers to the use of solid waste rich in calcium and magnesium to mineralize CO_2 and produce chemical products. There are three main challenges. The economic cost is high and the emission reduction benefits cannot be achieved. The technical aspect is that the geological exploration of the storage step is uncertain and the unstable utilization of CO_2 resources leads to excessive energy consumption. The environmental aspect is that the lack of technology and irregular geological movements will increase the probability of engineering accidents, leading to the deterioration of the ecological environment.

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