Carbon Capture, and Storage Technologies and Representative Cases Analyses

Jiawen Li[1,*], Fei Peng[2] and Xin Zhou[3]
[1]School of Design and Art, Lanzhou University of Technology, Lanzhou, 730000, China
[2]Faculty of Science and Engineering, University of Nottingham Ningbo China, Ningbo, 315100, China
[3]Melbourne School of Design, The University of Melbourne, Melbourne, 3052, Australia

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Abstract: As carbon dioxide (CO2) emissions increase, carbon capture and storage (CCS) are crucial for achieving sustainable growth and addressing climate change issues. This article explores the current application status of CCS technology. The focus is on three aspects: carbon capture, carbon storage, and carbon transportation. Including the development prospects of technology and the significance of research. And explore the practical application of CCS technology by introducing application cases of CCS in the United States, Norway, and Japan. At present, carbon sequestration technology is relatively mature, mainly including marine sequestration, oil and gas reservoir sequestration, and gas reservoir sequestration. However, due to the low concentration and pressure of CO2 emissions from power plants, it is difficult to reduce the energy consumption and cost required for carbon capture. Although many countries are currently engaged in CCS research. However, there are still many problems such as CO2 leakage during storage, high construction and operation costs, and immature technological processes. Further research and practice are needed.

1 INTRODUCTION

The challenge of reducing global carbon dioxide (CO2) emissions involves the collective efforts of nations across the globe. According to a 2022 report by the International Energy Agency (IEA), global CO2 emissions from energy-related sources hit a new high of 41.3 billion metric tons. With energy combustion and industrial processes accounting for 89% of total greenhouse gas emissions from energy, they stand as the leading sources of CO2 emissions. Global CO2 emissions are trending rising, which emphasizes how urgently more comprehensive and effective emission reduction policies are needed. To address the urgent problem of climate change and achieve sustainable growth, it is imperative that carbon emissions be reduced internationally. Interest in carbon capture and storage (CCS) technologies is high because of the pressing need to reduce greenhouse gas emissions, which has emerged as a major social issue.

Around the world, carbon capture technology are spreading throughout a number of industries. According to BNEF's Carbon Capture, Utilization and Storage Market Outlook 2022, the world's capacity to capture CO2 would expand sixfold by 2030, reaching an annual capacity of 279 million tons (Studies, 2011). The energy and electricity sectors are the main objectives of carbon capture technologies, particularly those with substantial CO2 emissions as thermal power plants and large industrial units. It is also used in the extraction and processing of oil and gas, which helps with efforts to reduce emissions. The use of carbon capture technology has increased due to the push to mitigate climate change and environmental concerns. Its application is being pushed by a number of nations and areas to reduce carbon emissions and advance sustainable development. Moreover, several international organizations and research bodies are deeply involved in researching and innovating in carbon capture technology, aiming to enhance its development and deployment. Advances in technology and reductions in associated costs are expected to further popularize carbon capture technology in the coming years.

* Corresponding author

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This paper provides a detailed analysis of CCS technology, covering its basic principles, applications, potential in cutting CO2 emissions, costs and viability, complex technical details, real-world examples, major challenges to its broad adoption, and possible approaches to address these challenges.

2 TECHNICAL PRINCIPLESS

With CCS, CO2 is captured from either point or dispersed sources and then stored underground for long-term disposal. Accordingly, CO2 is no longer emitted into or captured from the atmosphere and is thus not effective as a greenhouse gas.

2.1 Carbon Capture

Carbon capture technology mainly collects the CO2 emitted by high carbon emitting enterprises and uses various methods to store it, avoiding the process of releasing this part of CO2 into the atmosphere. The main methods are: Pre-combustion capture,Post-combustion capture and oxy-combustion.

2.1.1 Pre-Combustion Capture

This method first uses oxygen or air to gasify raw materials such as coal and biomass fuel before entering the combustion section for reaction. At the same time, a certain amount of water vapor is introduced, ultimately forming CO2, CO, H2, N2 and sulfides. The current high pressure of the mixed synthesis gas (about 30 – 50 atmospheres) makes it considerably simpler to separate CO2. Lastly, before moving on to the next phase, CO2 is compressed and delivered using methods such membrane separation, adsorption, and absorption. The residual gas is recycled (CO, H2, etc.) or emptied (N2, etc.) (Ju et al., 2021).

2.1.2 Post-Combustion Capture

It is captured following the combustion phase of the process, as the name implies. This technique is frequently applied in power plants, where the combustion segment is frequently followed by an absorption and separation mechanism. A solvent is used to absorb CO2, which is then blown out and compressed before entering the transportation pipeline (Paltsev et al., 2021).

2.1.3 0xy-Combustion

By using pure oxygen to burn the fuel, this approach primarily removes nitrogen and oxygen from the air, increases the purity and efficiency of CO2 combustion, and decreases the amount of CO and other byproducts produced. After years of development, this technology has been widely applied in various industries, such as the refining industry, the cement industry, the steel industry, etc.

In conclusion, carbon capture technology controls CO2 emissions at the source. These collection technologies can also provide good prerequisites for the subsequent transportation, storage, and utilization of CO2.

2.2 Transportation

There are three methods of transporting CO2: tanker, ship, and pipeline. For large-scale, long-distance transportation, pipeline transportation is the most cost-effective method of CO2 transportation.

2.2.1 CO2 Gas Pipeline Transportation

CO2 remains in the gas state in the pipeline, through compressor to increase pressure, and becomes gas. The majority of the CO2 in the gas well is in the supercritical phase, and in order to meet the criteria, it must be depressurized and throttled.

2.2.2 CO2 Liquid Pipeline Transportation

The CO2 holds the liquid in the pipe and is pumped to overcome friction and topographic elevation. However, the operating pressure of the pipeline is low, and the insulation layer is usually required, so the input cost is high.

In conclusion, gas transmission is easy to use and safe, but it is not economical. These two forms of transportation are appropriate for low throughput and short-distance travel; liquid transportation is likewise safe but requires a higher initial investment than gas transportation.

2.3 Carbon Storage

Carbon storage technology is a step after carbon capture technology and carbon transportation. Mainly storing the collected CO2. Avoid its emission into the atmosphere. The main methods are: Biological carbon sequestration 、 Marine sequestration and Geologic Sequestration.

2.3.1 Biological Carbon Sequestration

This method uses the photosynthesis of plants to convert CO2 into carbohydrates, which are fixed in the plant body or soil in the form of organic carbon. The greatest "carbon pool" on earth, the forest serves as the foundation of the terrestrial ecosystem and is crucial in controlling the climate and reducing global warming. It is a method of carbon sequestration with the lowest cost and fewest side effects. It is the most promising solution to global warming.

2.3.2 Marine Sequestration

There are two main types of marine sequestration: dissolution type and lake type. Dissolved Marine sequestration is the transport of CO2 to the deep sea, allowing CO2 to decompose naturally and become part of the natural carbon cycle. Lake-type Marine sequestration means that CO2 is sent into the deep sea 3,000 meters underground, because the density of sea water is less than the density of CO2, so it will become liquid at the bottom of the sea, becoming a CO2 Lake, which delays the process of CO2 decomposition into the environment.

2.3.3 Geologic Sequestration

One way to store carbon is to inject CO2 into a sandstone layer about 200 meters, which called Utsira. The rock stratum does not contain any commercial value like oil or gas, it is simply filled with salt water. Due to buoyancy effect, the injected CO2 moves from the injected location and eventually collects under the overburden (Torp and Gale, 2004). Utsira sandstone has high porosity and permeability. Therefore, CO2 can quickly migrate sideways and up through the rock layer, displacing water between the grains. Many sandstone's Bunter domes have faults, but if they are well sealed, they can form structural traps that can hold and store large amounts of CO2 (Williams et al., 2013). In rock stratum containing salt water, the dissolution of CO2 is a key factor. The solubility of CO2 in salt water is as high as 53 kg/m3, so the dissolution of CO2 also makes an important contribution to carbon storage. According to estimates, Utsira could be filled with about 600 billion CO2, which is equivalent to the total CO2 produced by humans in 20 years.

In conclusion, the captured and collected CO2 can be stored and utilized. The storage of CO2 mainly relies on the absorption of CO2 by plant photosynthesis and the sequestration of CO2 to the seabed or underground. It is not yet known whether the CO stored on the seabed and underground will have an impact on the soil and marine environment. Further research and practice are needed.

3 THE CASES FOR CCS TECHNOLOGIES

Many developed and developing countries have actively explored and attempted carbon capture technologies. However, the national conditions and forms of carbon emissions vary among countries. Therefore, different countries have different approaches to CCS. These countries are actively exploring ways to capture, transport, and store carbon. To achieve economic maximization while reducing carbon emissions. However, many countries' explorations are based on theoretical aspects and require relevant practice to prove their feasibility. Here are three cases of CCS in different countries to understand the practice and application of CCS technology from three different regions: the United States, Europe, and Asia.

3.1 The United States

The Petra Nova project in Texas serves as a prominent demonstration project of CCS in the United States. Launched as a collaboration between NRG Energy and JX Nippon Oil & Gas Exploration in operation in January 2010, the Petra Nova CCS Project is the only two commercial-scale coal-fired power plants which deploy CCS technology in the world. The project uses a well-established carbon capture technology, jointly developed by Mitsubishi Heavy Industries, Ltd. (MHI) and the Kansai Electric Power Co. The technology uses an advanced solvent which effectively absorbs and releases CO2. After capture, CO2 will be compressed and dried, and then transported through an 80 miles pipeline to Hilcorp's West Ranch oil field near Vanderbilt, Texas. Here, the CO2 is used for enhanced oil recovery (EOR) and finally sequestered (Office of Fossil Energy and Carbon Management, 2020).

The project is specifically targeting post-combustion carbon capture, a solution allowing separation of CO2 from domestic exhaust gases after fossil fuel combustion. This method is particularly useful as it allows vegetation to be restored existing ones and does not require to change their operational fundamentals. The Petra Nova system captures more than 1.6 million tons of CO2 per year, making it the world's largest project linked to a power plant.

3.2 Norway

Norway's Sleipner project is in the middle of the North Sea，and near the border line between United Kingdom and Norway (Torp and Gale, 2004). This project is the world's first commercial CO_2 injection project, and it demonstrates that CO_2 capture and storage is an effective way to mitigate climate change.

Unlike other oil fields, which exhaust extracted CO_2 directly into the atmosphere, Sleipner project will inject extracted CO_2 underground. Then injected through a separate well into an aquifer more than 1,000 meters below the seabed (Kongsjorden and Torp, 1997). Underground space in the European Union and Norway can store about 80 billion tons of CO_2, which is about 1.4 times the total CO_2 that has accumulated in the atmosphere since the industrial era. The Wells were designed to cross through the natural fractures and may have hydraulic stimulation of the fractures in the reservoir to help capture more CO_2 (Eiken et al., 2011). It has four platforms, and the Sleipner Vest field is used as a facility for CCS which is the first offshore CCS plant in the world. Since the project began several years ago, the accumulation of pressure in the reservoir has been small and the pressure is slightly higher than that of hydrostatic pressure.

3.3 Japan

CCS plays a crucial role in Japan's energy strategy. The Japanese government requires the introduction of CCS technology to collect and store CO_2 generated by thermal power generation. And achieve carbon neutrality before 2050. For CCS, efforts should be made to design a roadmap for technology development, cost reduction, and the development of suitable sites. Unlike other countries, the Japanese government is also committed to conducting demonstration tests on the transportation of liquid CO_2 by ships. And optimize the network between CO_2 emission sources, recycling, and storage facilities (Abe et al., 2013).

The geographical CO_2 storage potential in Japan's coastal areas is significant, with approximately 150,240 billion tons. The CO_2 storage capacity in water bodies with a depth of less than 200 meters can reach 146 billion tons. The CO_2 storage capacity in water bodies with depths of 200-1000 meters can reach 90 billion tons. This storage capacity is very considerable.

The challenge for Japan to promote the development of CCS technology lies in the transportation of CO_2. The industrial areas with high CO_2 emissions in Japan are mainly located in the coastal areas on the Pacific side. The areas suitable for storing CO_2 are mainly located on the side of the Sea of Japan. The distance between the two is too long and is not suitable for pipeline transportation. Therefore, Japan plans to use ships for the transportation of liquid CO_2. Since no country has previously implemented the transportation of liquefied CO_2 through ships at low temperatures and pressures. Therefore, Japan took the lead in demonstrating this practice (Baskoro et al., 2022).

4 TECHNICAL BARRIERS AND CHALLENGES

CCS technology, a key strategy in the fight against climate change, aims to capture CO_2 emissions from sources like power plants and industrial facilities before they reach the atmosphere, and then store them underground in geological formations. While CCS offers a promising path to reduce greenhouse gas emissions and mitigate global warming significantly, there are still some challenges, which span a variety of domains, affecting the scalability and effectiveness of CCS as a comprehensive solution to climate change.

One of the primary limitations of CCS technology lies in its capture efficiency and the energy required for the capture process. Current CCS technologies cannot capture 100% of the CO_2 from power plants and industrial sources, which leave a substantial amount of emissions unaddressed (Shen et al., 2022). Even International Energy Agency, an active supporter for carbon reduction, doubts the effectiveness and the large-scale of viability of CCS. Moreover, the process of capturing, compressing, transporting, and storing CO_2 is energy-intensive, requiring a substantial amount of the energy produced by the plants it aims to make cleaner. Davoodi et al.argued that a coal power plant with CCS devices would consume 25% more energy for operation (Davoodi et al., 2023). Given that extra energy requirement and potential leakage downstream, it cannot be proved that all CO_2 is captured. Both the capture efficiency and additional energy needs bring significant challenges for CCS technology and doubters may view that unreliable.

In practice, high initial investment and more operating costs is another important factor influencing its massive deployment. Such cost can arise from capture equipment, transportation infrastructure, and storage site development and operation. For example, the power generation costs for a coal power plant with carbon capture facilities would rise by an additional \$20 to \$100 per ton, which diminishes the benefits derived from reducing emissions and influences the commercial viability of CCS demonstration projects (Burger et al., 2024). In addition, extra expenses associated with enhanced transportation and storage requirements pose important constraints for the use of CCS. Pipeline transportation is currently regarded as the safest and the most effective way of CO2 transportation (Rashid et al., 2024). Pipelines transporting CO2 have higher standards for corrosion resistance, which increases the procurement costs and operation and maintenance costs and significantly influences the whole CCS value chain. The storage of CO2, as an important stage, also incurs high cost as well as stringent safety requirements (Ratanpara et al., 2023). Three main carbon storage ways are salt water layer storage, oil and gas layer storage and gas layer storage. The first two storage methods require necessary infrastructure development, including the construction of injection wells, surface facilities for monitoring and regulation, and possibly pipelines leading to the storage site (Ratanpara et al., 2023). The engineering and material costs associated with the construction of these facilities are considerable. While the gas layer storage is still in early stage of development, which requires substantial funding for further research (Yusuf and Ibrahim, 2023).

The aim of CCS is to reduce environmental impacts and mitigate climate change by decreasing atmospheric CO2 levels, but risks associated with the technology are not fully understood and this occurs within the whole process of CCS. For example, the construction and operation of carbon capture facilities can have environmental repercussions and pose risks to health and safety due to the compression of CO2. This process also results in the production of carbon oxides, SO2, and other chemicals. Besides, the storage of CO2 may significantly influence local climates, destroy regional ecologies, and pollute groundwater. The injection of CO2 into geological formations evens trigger seismic activity in some areas. The safety and sustainability of underground CO2 storage is crucial for the application of CCS (Sun et al. 2018).

5 CONCLUSION

This article introduces CCS technology in detail focusing on three aspects: carbon capture, carbon storage and transport. Including the development prospect of technology and the significance of research. Through introducing the cases of CCS applications in the United States, Norway and Japan to study deeper about CCS technology. CCS is widely recognized as a key way to mitigate global warming and makes an important contribution. CCS consists of two components: carbon capture and carbon storage. Carbon capture is divided into pre-combustion capture, post-combustion capture and oxygen-rich combustion capture. However, due to the lower concentration and pressure of CO2 emitted by power plants, the energy consumption and cost of either technology are difficult to reduce. The technology of carbon sequestration is relatively mature, mainly including Marine sequestration, oil and gas reservoir sequestration and gas reservoir sequestration. Japan ships CO2 captured, recycled and liquefied from a power plant in Kyoto to a storage site near Hokkaido. The High Temperature DAC process captures CO2 directly from the air. Norway's Sleipner inject CO2 into a sandstone layer about 200 meters, which called Utsira. Petra Nova's system inject carbon CO2into the oil field for EOR, enhancing oil recovery while ensuring the CO2 is securely stored underground. In addition, by measuring existing technologies in certain countries, we can use these data to identify possible potential ways to improve CCS technology and adjust for the shortcomings of current technology. Although many countries are now engaged in CCS research, there are still many problems to be solved and many technical problems have not been broken through.

AUTHORS CONTRIBUTION

All the authors contributed equally and their names were listed in alphabetical order.

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