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Research Progress on Carbon Dioxide Capture and Storage

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Abstract. Carbon capture and storage (CCS) is widely considered as one of the most effective strategies for reducing greenhouse gas emissions and addressing climate change. This article reviews the basic theories, mechanisms, and prospects of CCS technologies in the background of carbon neutrality. The article begins by outlining the natural and anthropogenic sources of carbon dioxide and their roles in the carbon cycle. Mainstream capture methods are analyzed with their working principles, advantages and limitations, mainly including physical adsorption, chemical absorption, and membrane separation. Innovation of membrane brings better performance and efficiency. The geological and ocean storage options are discussed, focusing on the feasibility, safety, and long-term potential. It also summarizes the increasing importance of advanced materials. However, CCS still faces economic, technical, and social challenges, including high costs, infrastructure requirements, and public acceptance. The article concludes that continuous technological development, policy support, and international cooperation are key to the widespread implementation of CCS and its contribution to promote global sustainable development.

Keywords: carbon dioxide, carbon dioxide sources, carbon capture and storage.

1. Introduction

The massive emission of carbon dioxide still puts a threat to the environment. The global warming caused by greenhouse gas emissions has led to climate change and continued to threaten the ecosystem, human health and the sustainable economic development. The most typical ways to accomplish the carbon neutralization and develop the green economy are energy conservation and emission reduction, which means to reduce the consumption of chemical fuel and decrease the emission of carbon dioxide. In all kinds of strategies, carbon capture and storage (CCS) has has been approved as one of the most promising technological solutions due to its great emission reduction capability, especially for industries that are difficult to decarbonize completely, such as power generation, steel, cement, and chemical manufacturing.

CCS is one of three mandatory emission reduction technologies in the four key emission reduction technology pathways published by the IPCC (The Intergovernmental Panel on Climate Change) in 2018 [1]. The IPCC has predicted that the cost of emission reduction in 2100 will increase by 130% compared with that in 2005 if CCS technology is not adopted [2]. According to International Energy Agency (IEA) and the Carbon Sequestration Leadership Forum (CSLF), the scale of carbon capture and storage in 2030 and 2050 should be 10-15 and 100 times more than in

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2020 in order to realize the net zero emission in 2050 for the energy sector. Many international organizations and climate models also pointed out that the CCS should be widely applied in order to achieve the net-zero target and control the global temperature. The importance of CCS is that it can prevent the CO_2 from large sources such as power plants and manufacturing factories before it enters the atmosphere and we can find a way to reduce the global warming and decarbonization without removing the industrial activities.

Essentially, CCS has three key stages: capture, transport, and storage of carbon dioxide [3]. In recent years, breakthroughs have been made in both the research and application of carbon capture and storage technologies. Over the past few decades, extensive research and development have produced several capture methods, such as post-combustion, pre-combustion, oxy-fuel combustion and industrial capture technologies [4]. Each method had distinct separation principles. Post-combustion capture relies on chemical absorption and it is presently the most widely used approach. Pre-combustion capture is more common in integrated gasification combined cycle (IGCC) systems, enables the removal of CO_2 before fuel combustion but typically requires more complex infrastructure. Oxy-fuel combustion burns fuel in pure oxygen instead of air and produces CO_2 in high concentration, which facilitates relatively straightforward separation but high costs for oxygen production. Industrial capture usually targets high-emission sources. In addition, the CO_2 capture also has innovative technologies, like adsorption using liquid and solid sorbents, membrane separation techniques and cryogenic distillation. Advancements have also been achieved in CO_2 transport infrastructure like pipeline and ship and storage safety. Despite deep saline aquifers, depleted oil and gas fields and unmendable coal seams on the ground, marine and chemical storage can also be considered.

CCS is crucial in capturing CO_2 emissions from large industrial sources. It can slow global warming and is valuable in climate change mitigation. CCS allows industries to continue using fossil fuels more responsibly while transitioning to renewable energy. It helps industries reduce their carbon footprint with normal operational efficiency. It provides a stable supply of energy as we begin our journey to a low carbon world and lessens our reliance on fuel imports. CCS technology can provide economic growth and job opportunities within a variety of sectors through innovation and investment. It maintains biodiversity and quality of air. It protects ecosystems from climate change.

However, costs, infrastructure development, regulatory responsibility and public acceptability are still significant barriers to be addressed. Given these challenges and opportunities, it is essential to take a systematic review and analyze the main methods of CO_2 capture and storage. By critically comparing different technologies, including their mechanisms, advantages, challenges, and prospects, the article aims to summarize the existing researches and provide valuable reference and inspiration for the researchers of CCS systems and facilitate the application of CCS technologies globally.

2. Carbon dioxide sources

2.1. Natural sources

Natural sources of carbon dioxide are parts of the Earth's carbon cycle. Carbon emission and absorption from these sources are generally balanced with no human intervention. Natural sources include the decomposition of organic substances, respiration, oceanic release, and volcanic activities.

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Organic substances such as dead branches and leaves, animal carcasses and food waste will be broken down into simpler inorganic substances by bacteria, fungi and other organisms. New enzymes are produced by microorganisms that break down large and complex macromolecules such as carbohydrates, proteins, and fats into smaller units. Small molecules will then be decomposed into even smaller ones through respiration or fermentation to produce CO_2 in an aerobic condition or CH_4 in an anaerobic condition and finally converting into carbon dioxide, water, inorganic salts and other compounds [5].

The definition of respiration is the process of oxygen and carbon dioxide exchange between the animal's blood and the environment. During respiration, animals, plants and microorganisms inhale oxygen and oxidize and decompose the organic matter in their bodies to release energy and carbon dioxide. Respiration also occurs at the cellular level. All plants and animals release carbon dioxide and water vapor into the atmosphere. Every cell in the body relies on respiration to fill the energy needs. This process is called cellular respiration. The respiratory process forms energy for the organisms by combining glucose with oxygen in the air. In cellular respiration, glucose and oxygen change into energy and carbon dioxide. So, during cellular respiration, carbon dioxide is released into the atmosphere.

The oceans are vast carbon reservoirs that continuously dissolve and release carbon dioxide. The CO_2 in seawater is in a dynamic equilibrium with the atmosphere. When the temperature of the seawater rises or the concentration of CO_2 in seawater becomes too high, CO_2 will be released back into the air.

Volcanic activities release a large number of gases including carbon dioxide. The Earth's mantle contains carbonate minerals and trapped carbon dioxide. As magma rises and pressure decreases, dissolved CO_2 escapes from the magma [6]. Large amounts of CO_2 are emitted into the atmosphere along with volcanic ash, lava, and water vapor when the volcanos erupt. However, the emissions from modern volcanic activities are relatively small compared with human activities.

2.2. Anthropogenic sources

2.2.1. Source of living

The source of daily life mainly refers to the carbon dioxide generated from individual or household activities. These emissions are usually directly related to daily necessities like clothing, food, housing and transportation. The CO_2 produced in human daily life is usually dispersed but also in large quantities.

Burning fossil fuels like coal and natural gas for electricity and heat is currently the biggest source of carbon dioxide emissions. Burning fuel for cars, ships and planes that burn gasoline or diesel is the fastest-growing source of carbon dioxide in many countries. Natural gas, liquefied petroleum gas (LPG) and coal are used for cooking, heating and providing hot water in houses and commercial buildings. When coal, natural gas, gasoline and oil are burned, the carbon in fossil fuels combines with oxygen in the air to produce carbon dioxide and water vapor.

Every commodity people purchase, such as clothes, electronic products, plastic products, generates CO_2 during the processes of raw material extraction, production and transportation. The food people eat also has a carbon footprint. The carbon footprint of meat and dairy products is much higher than that of vegetables and fruits because livestock farming causes a lot of methane and carbon dioxide to be released into the atmosphere. The decomposition of household waste in landfills produces CO_2 and methane. Waste incineration directly emits CO_2.

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2.2.2. Source of production

The main sources of production refer to the carbon dioxide generated in social and economic production fields such as industry and agriculture. These emissions are produced to provide the energy, products and materials necessary for the operation of society [7].

Some industrial chemical reactions themselves produce large amounts of carbon dioxide. The key step in cement production is to heat and decompose limestone ($CaCO_3$) into quicklime (CaO) and carbon dioxide (CO_2). The calcination process directly releases substantial CO_2. In the process of steelmaking in blast furnaces, coke is used as a reducing agent to reduce iron ore into metallic iron, generating significant CO_2 emissions. When producing chemical products such as fertilizers, plastics and synthetic fibers, some chemical processes also emit carbon dioxide.

Cargo ships, freight trucks, freight trains and cargo planes serving the global supply chain burn fossil fuels. They transport raw materials and goods to all parts of the world. Coal-fired and gas-fired power plants burn large amounts of fossil fuels. They generate electricity and heat and become the world's largest producer of carbon dioxide.

When forests are cut down or burned for farmland, pastures or cities, the trees will lose their ability to capture carbon dioxide and the carbon stored in the trees will also be rapidly released into the atmosphere in the form of carbon dioxide through burning or rotting. Some agricultural practices such as wetland drainage with excessive soil tillage and chemical fertilizers can also lead to the oxidation and release of carbon stored in the soil.

3. Carbon capture and storage

3.1. Capture technologies

3.1.1. Physical adsorption

Physical adsorption refers to a method of capturing CO_2 in which gas molecules adhere to the surface or pores of solid materials through van der Waals forces or weak electrostatic interactions, without undergoing any chemical reaction. This process is efficient and reversible. Practically, solids that can hold a certain amount of gas molecules are called adsorbents which can be used to capture specific gas molecules selectively. Regeneration is essential to recover their ability through washing, drying and heating since adsorbents lose effectiveness after repeated use. The retained CO_2 are released during the regeneration process, making the process cyclic and reusable.

Some typical adsorbents include activated carbon, zeolites, and silica gel [8]. Activated carbon is porous and has large surface area. It is chemically stable and adsorbs CO_2 through van der Waals forces. It is also fast response, widely applicable and recyclable. It is relatively easy and cheap to regenerate. Heating is usually used to regenerate activated carbon. Zeolites are aluminosilicate materials with ordered pores. It has good chemical and thermal stability. It adsorbs CO_2 through electrostatic interactions and has high selectivity for CO_2 from gas mixtures. Silica gel is widely used due to its thermal and chemical stability. It adsorbs CO_2 based on the number and distribution of surface hydroxyl groups. Surface modification that adds functional groups or controls pore sizes can further improve the affinity and efficiency of silica gel in CO_2 adsorption.

Physical adsorption can be applied in post-combustion capture from flue gas in coal-fired power plants, steel mills and cement factories. zeolites or activated carbon can be used to remove CO_2 in natural gas processing to decrease the CO_2 content and improve the methane purity. In chemical plants, CO_2 in exhaust gases can be recovered for further use or to decrease emission. The

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advantages of this method include wide operating conditions, simple process, relatively low regeneration energy and recyclable adsorbents with less environment impact. However, the physical adsorption has some disadvantages, such as low capacity, saturation, relatively low selectivity compared with chemical absorption, poor performance at low CO_2 content and poor stability at high temperature and high humidity.

3.1.2. Chemical absorption

Chemical absorption involves separating CO_2 from gas mixtures through chemical reactions with liquid absorbents, forming new compounds in new compounds beyond simple dissolution and chemical bonding. In principle, the CO_2 contained in a mixed gas reacts with the alkaline absorbent solutions and regeneration is reached by lowering pressure or raising temperature. Ammonia solutions, strong alkaline solution and aqueous alkanolamines are typical absorbents.

One of the biggest advantages of chemical absorption is that it is possible to absorb even low concentration CO_2 with a high efficiency. The technology is well developed and widely used in power plants and chemical industries. However, it has drawbacks such as high energy consumption, limited regeneration cycles, and equipment corrosion. Among all absorbents, amine-based solutions are most widely applied. Their amino groups react reversibly with CO_2, forming carbamates or bicarbonates. Alkaline solutions like NaOH, KOH, and $NH_3 \cdot H_2O$ can also absorb CO_2 to form carbonates or bicarbonates [9]. Similarly, carbonate solutions like potassium carbonate react with CO_2 and water to form $KHCO_3$.

3.1.3. Membrane separation

Membrane separation is based on the differences in permeability of various gas molecules through a membrane to separate CO_2 from a mixture. The separation depends on the solubility, diffusivity, and permeation rates of the molecules in the membrane material. CO_2 usually dissolves and diffuses faster in certain polymers or inorganic membranes so it can pass through the membrane more easily. A pressure gradient across the membrane drives the separation process.

Separation efficiency is influenced by factors such as gas composition, pressure, membrane selectivity, and structure. Membranes types include mixed-matrix, facilitated transport, inorganic, and polymer membranes [10]. Membrane separation offers advantages like low energy consumption, compact equipment and easy maintenance. Unlike adsorbents, membranes do not need regeneration and have high capture efficiency. However, the drawbacks for membranes include high manufacturing costs, limited lifespan, low efficiency at high temperature and corrosive gases or water vapor. These problems limit the industrial application of membranes.

Currently, inorganic membranes like metal or ceramic-based porous membranes, are mainly used in laboratory research. Surface modifications and functional group additions can improve their selectivity. In contrast, polymer membranes are porous plastics with controlled microstructures and certain functional groups like amines to increase the affinity and efficiency of CO_2 capture. Researchers are focusing on developing inexpensive and highly performing materials for industrial use in the future.

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3.2. Storage technologies

3.2.1. Geological carbon storage

Geological storage refers to compressing captured CO_2 into a supercritical fluid and injecting it into geological formations at certain depths below the earth crust for long-term storage under impermeable caprocks. The temperature at which CO_2 exists as a supercritical fluid must be higher than 31°C and the pressure must exceed 7.38 MPa, which usually requires injection take place at depths greater than 800 meters [11].

The main geological formations for storage are depleted oil and gas reservoirs, deep saline aquifers, and unmendable coal seams. Depleted reservoirs are ideal because they typically have excellent sealing properties and well-documented geological data, reducing risks. Additionally, CO_2 can act as an enhanced oil recovery agent, pushing out residual oil [12]. Deep saline aquifers in sedimentary basins are suitable because the brine in them is stagnant and unusable. The injected CO_2 will dissolve in the brine and may have certain interactions with water or rock minerals, which helps long-term storage. Suitable aquifers are located at 800–3500 meters below the earth crust, separated from drinking water sources by low-permeability caprocks such as shale. Unmendable coal seams can also store CO_2 through diffusion and adsorption in coal pores. However, their effectiveness depends on coal thickness, maturity, sealing conditions, and geological structures.

3.2.2. Ocean carbon storage

Ocean carbon storage technology refers to the use of the ocean as a carbon sink, where CO_2 is stored in seawater or marine sediments through physical, chemical, or biological processes, thereby delaying its release into the atmosphere. Different approaches have been developed, such as injecting CO_2 into the water column through pipelines or transport ships so that it dissolves naturally, or depositing it at depths greater than 3000 meters to form a dense CO_2 lake on the seafloor. Another method enhances carbonate reactions. When alkaline substances such as limestone or carbonate minerals are added into the ocean, they can mitigate ocean acidification and enhance the absorption capacity of seawater [13]. Compared with other storage methods, the capacity of ocean carbon storage is large at relatively low cost and the offshore sites of oceans are far away from cities and areas with fresh water, which makes it safer [14]. Even if leakage occurs, the CO_2 will firstly enter the seawater, where it can diffuse and disperse in the seawater. So that if the situation is discovered in time, timely management can avoid serious consequences.

4. Future prospects of carbon dioxide capture and storage

Low-carbon and environmental protection are the development directions that all countries are striving for. Meanwhile, as people's awareness of environmental protection continues to rise, the development and utilization of various new energy sources have become research hotspots in all countries. Carbon capture and storage (CCS) is one of the most hopeful technologies to reduce greenhouse gas emission on a large scale. With the large proportion of coal in the world’s energy structure and globally increasing energy demand, CCS is taking an important role in mitigating climate change and completely control the greenhouse gas emission in the current situation. It also helps to achieve the low-carbon and intensive use of high-carbon resources such as coal and oil, promotes the transformation and upgrading of high-emission industries such as power, coal chemical engineering, oil and gas, also drives the development of other related industries. The future of CO_2

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capture and storage will depend on continuous innovation of technology and effective cost reduction strategy as well as the transformation of industry based on the environment.

At present, the major carbon dioxide capture technologies include chemical absorption, physical adsorption, and membrane technology. Among them, chemical absorption is the most mature and widely used method. It has reliable performance, but high regeneration energy and solvent degradation. Physical adsorption and membrane separation have obvious advantages in reducing energy consumption, but their application in large industry is limited due to the performance fluctuation and material problems.

The Metal-Organic Frameworks (MOFs) will change the situation. The metal-organic framework is regarded as the next generation material for carbon dioxide absorption due to the tunable porosity and large surface area. In recent years, the development of porous liquid based on MOFs combining absorption and adsorption properties shows the possibility of improving selectivity and reducing energy loss. Hybrid approaches such as chemical-looping, cryogenic separation and electrochemical technology are also being developed and explored. They provide more technical paths and more flexible solutions.

However, the economic barrier is still the biggest challenge for the development of CCS. The absorption system has a high energy requirement for solvent regeneration, which means a large amount of energy will be consumed in the process. The advanced adsorbent and membrane material will also lead to an increase in cost. It is expected that the future cost reduction strategy will focus on the following three aspects: extending the service life of materials by improving their performance to reduce the frequency of replacement, combining the process of capture and industrial process to reduce the loss of energy and carrying out large demonstration project to achieve the economy of scale. Moreover, carbon dioxide can be used as feedstock for producing fuels, building materials and high-value chemicals after capturing. By converting the carbon in the atmosphere into an industrial resource, it not only reduces the cost of carbon capture, but also provides new market for low carbon industry.

Based on the analysis above, carbon dioxide capture and storage may have three future trends. One is the integration with renewable energy like hydrogen production and even more with energy storage systems. Carbon-neutral or carbon-negative processes can be achieved. Another is the digitalization. Artificial intelligence and process simulation will be applied to the design of capture system and operation parameter control to realize more accurate and intelligent capture processes. Furthermore, international cooperation will be continued. As climate change is a transnational issue, joint researches, technology exchange and cross-national demonstration projects will accelerate the application of advanced CCS technologies. Last, policy and market will create favorable conditions. With the carbon price, subsidy policies and green finance, the cost of carbon dioxide capture and storage will be controlled and large-scale application will be promoted.

In summary, carbon dioxide capture and storage is a highly technological, economically mature and environmentally friendly industry. Although there is no technology that can satisfy both high efficiency and low energy consumption now, the carbon dioxide capture and storage technology has shown a good prospect with the development of new materials, hybrid processes and integrated technologies. By solving the cost issues and enhancing international cooperation, CCS will become a general technology to realize global carbon neutrality and promote sustainable development.

5. Conclusion

Carbon capture and storage (CCS) is is an essential enabling technology for improving carbon emissions. It allows the energy-intensive industries like power, steel, cement and chemical to

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drastically reduce their emissions while the rest of the energy shifts towards renewable energy. Its capability to reduce emissions while keeping the economy stable is one of the most realistic and essential tools in the arsenal of combating climate change.

Evaluating CCS requires examining its two main components: capture and storage. For capture, current technology is dominated by chemical absorption which can provide reliable efficiency but with high energy demand. Physical adsorption using activated carbon and zeolites can reduce the energy demand but limited by its selectivity and regeneration. With increasing technology maturity of polymer and hybrid membrane technology, membrane separation is expected to be a compact and flexible solution with promising performance in cost reduction and scalability. In general, capture technology is focusing on improving efficiency and economics, but breakthrough in new materials and process integration is still needed.

For storage, geological storage options, including depleted oil and gas reservoirs and saline aquifers, are the most mature and safe with the existing monitoring system that can ensure the long-term storage. Ocean storage has a huge capacity but many ecological and ethical issues need to be resolved before any commercial application. Mineral carbonation is still in its early stages of development but has a promising potential in the long term by permanently lock carbon dioxide in stable solid compounds. Currently, there are many technologies available for storage and they are at different levels of maturity. However, geological storage will continue to be the main option for the foreseeable future.

CCS is not a perfect technology but it is a needed step in the right direction. Capture technology is moving towards better efficiency while storage technology is providing more reliability and capacity. To optimize the potential of using CCS, advances in technology innovation, large scale deployment and supportive policies will be needed. With continued international collaboration, CCS can turn carbon from an environmental problem into a manageable resource that will enable sustainable development towards a low-carbon future.

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