Technological Progress and Practical Prospects of Carbon Capture and Storage and Utilization

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Abstract. Global warming is one of the unavoidable hot topics in today's world. It is expected that by 2025, the continuous rise in temperature will still be a major challenge for humanity. To survive, humanity must curb the continuously rising temperature. Among them, the large-scale emission of carbon dioxide is generally regarded as the main cause. Therefore, countries around the world have taken measures one after another to strive to reduce carbon dioxide emissions and lower its concentration in the atmosphere. Carbon capture, utilization and storage (CCUS) technology, as a novel and promising means of emission reduction, has attracted widespread global attention. This article mainly introduces how this technology, which is being actively promoted, has been carried out, what breakthroughs have been achieved, and what benefits it has brought to practical applications. On this basis, the challenges that CCUS will face in its future development were analyzed. For various industries, how should CCS technology be combined with other industries to maximize its own advantages and achieve sustainable development.

Keywords: CCUS, capture, utilization, transport, storage.

1. Introduction

With the development and progress of The Times, human life has become increasingly convenient. For instance, you can almost go anywhere in the world because of the invention of transportation means such as airplanes and cars. Tall buildings and skyscrapers are everywhere. When walking on the road at night, you no longer need to rely on the light of the stars because there are streetlamps now. Behind this, we can see the development of chemical engineering, agriculture and construction. These human activities not only bring about positive aspects but also lead to global warming and This leads to an increase in the content of carbon dioxide in the atmosphere compared to before. According to NASA's data, Due to human activities, the average temperature on Earth has begun to rise by approximately 1 degree Celsius [1]. However, this is not over. Up to now, this figure is still rising rapidly at a rate of 0.2 degrees Celsius every ten years. Most of these gases that cause the temperature to rise are carbon dioxide, accounting for more than 400ppm in the atmosphere [1]. According to the data analysis of the Global carbon budget, the global carbon budget predicts that fossil carbon dioxide emissions will reach 37.4 billion tons in 2024, an increase of 0.8% compared with 2023 [2]. That is to say, the content of carbon dioxide was still increasing a year ago, although we all urgently knew that emissions needed to be reduced to prevent the continuously rising temperature [3].

First of all, we need to know what human activities cause carbon dioxide emissions, such as the use of fossil fuels, as well as transportation in daily activities, the use of electric lights, and deforestation. Among them, the use of fossil fuels and deforestation have almost become the main contributors to carbon dioxide emissions. A series of problems brought about by global warming also affects the ecological environment [3]. The rise in ocean temperature, having absorbed a large amount of heat, has led to a rise in sea levels. The number of ice sheets in Antarctica is gradually decreasing, glaciers around the world are retreating, and the size and thickness of sea ice in the Arctic are both shrinking [4]. The frequency of extreme weather has increased, and these phenomena all remind humanity that it is necessary to find rapid and effective countermeasures in the short term to slow down the pace of global warming [5]. China mentioned: "China will enhance its nationally determined contributions, adopt more forceful policies and measures, and strive to peak carbon dioxide emissions

before 2030 and achieve carbon neutrality before 2060." Shortly after Biden took office, the United States also called on government leaders around the world to take action and measures and hoped to achieve the goal of reducing greenhouse gas emissions by 61% to 66% by 2035 compared with the level in 2005 [6]. The new trend in the development of CCUS technology is regarded as an important means to reduce greenhouse gas emissions and address global climate change in the future [7]. As the name suggests, this technology refers to the capture and storage of carbon dioxide before it enters the Earth's atmosphere.

As to achieve the goal of mitigating climate change, the specific method is to prevent the large-scale emission of greenhouse gases from intensifying global warming and environmental damage. In the process of carbon dioxide storage, it can be classified into two types, namely Marine storage and geological storage. Geological storage is a more popular and frequently used method compared to Marine storage at present. Carbon dioxide is absorbed from the atmosphere, and, over time, it transforms into carbonate minerals through chemical reactions in salt-containing aquifers, facilitating storage. CCUS has received extensive attention in recent years due to its ability to both store and rationally utilize carbon dioxide. At present, there are over 30 CCUS projects underway worldwide. This includes North America and Europe. Despite the rapid development of renewable energy, fossil energy (coal, oil and natural gas) will still dominate the world's energy structure in the short term.Especially in high-emission industries such as power, steel, cement and chemical engineering, carbon emissions are difficult to be rapidly eliminated merely by relying on the replacement of renewable energy. Therefore, CCUS technology, as a "transitional period" means of carbon reduction, is regarded as an important technical path to achieve the goal of carbon neutrality. This means that this technology has gained widespread recognition worldwide.

2. The Basic Príncipe of CCUS Technology

2.1. Traditional CCUS Methods

The purpose of carbon capture technology is to collect the carbon dioxide before it enters the atmosphere. Traditional carbon dioxide capture technologies, generally speaking, include post-combustion capture, pre-combustion capture, and oxygen-enriched combustion [7]. These three technologies can be respectively applied to different scenarios, such as in power plants and other industrial facilities. Post-combustion capture is the most common type. According to the name of this technology, it involves burning fossil fuels, which are then converted into electrical or thermal energy. This is the measure taken by factories to generate electricity. The gas produced subsequently contains carbon dioxide, and carbon capture technology plays a significant role in this process. Pre-combustion capture can remove carbon dioxide in advance before the combustion of fossil fuels [8]. By chemically reacting the gas and using a gasifier to ensure that part of the fuel is oxidized, a mixed gas of hydrogen and nitric oxide is produced. Then, water is used to convert carbon monoxide into carbon dioxide. The main method of oxygen-enriched combustion is to utilize pure oxygen and dilute it with recovered carbon dioxide or water. Thus, when coal is burned in an oxygen-enriched environment, the main products produced are carbon dioxide and water. Carbon dioxide can be captured by condensing the water in the exhaust gas.

2.2. The process of carbon separation technology

Whether it is capturing carbon dioxide before combustion or capturing dioxygen after combustion, the indispensable step is to separate carbon dioxide from other gases or products, so that carbon dioxide can be extracted. At present, there are several popular processes for separating carbon dioxide. The first step is to directly capture carbon dioxide from the air (DAC) [9]. In factories, huge machines that can draw in air are used to remove carbon dioxide through chemical means. Chemical means are currently a relatively mature and widely applied technology, which can be used in industries such as cement and power generation. Because this technology can directly reduce carbon dioxide in the atmosphere, it has also attracted attention in China [9]. This capture technology can be used to collect

carbon dioxide produced by small fossil fuels or during transportation, which is different from capturing carbon dioxide emitted by fixed large industries. Therefore, this approach can be regarded as a remedial measure to deal with the situation. Due to its low cost and high efficiency, under the current development achievements, almost all adsorption materials are low-cost. For instance, solid crystals like hydrogen-bonded organic frameworks can be used as adsorption materials to directly collect carbon dioxide from the air under atmospheric pressure at a specific temperature. They can be roughly divided into carbon absorption, carbon adsorption and membrane absorption. Carbon absorption refers to the reaction between carbon dioxide and specific chemical substances [10]. The formation of new substances is usually unstable salts, which will produce carbon dioxide again when heated. Adsorption method involves using materials for adsorption and then separating carbon dioxide through chemical reactions during the adsorption process. Aqueous amines utilize this technology to separate carbon dioxide [11]. They adsorb carbon dioxide through amine substances in industrial production and then separate the carbon dioxide from them.

In addition, there is the use of membrane gas separation, where carbon dioxide and other gases are separated through permeable materials, and most of them are subjected to low-temperature treatment to obtain carbon dioxide. The fundamental principles used in physical and chemical methods are different, but there are similarities in the types of methods [12]. Physical methods are based on the basic characteristics of carbon dioxide, such as changes with pressure or temperature, and thus use adsorbents to capture carbon dioxide [12]. In addition, the difference lies in low-temperature distillation, which can change the physical form of carbon dioxide, such as liquefaction or solidification. Separate the carbon dioxide by distillation.

The principle of bioenergy (BECCS) is based on the characteristic that plants need to carry out photosynthesis during their growth to maintain life. Therefore, they can absorb carbon dioxide and produce oxygen as a by-product. This process utilizes wood or grass to remove carbon dioxide from the air through photosynthesis during their growth.

3. Carbon Transport Technology

Carbon transportation is an important step that occurs after carbon dioxide is captured, facilitating its subsequent utilization or storage [13]. At present, the transportation methods mainly rely on means of transportation such as ships and vehicles, or the common pipeline transportation. This is similar to the long-distance transportation of natural gas. Therefore, the transportation by means of transportation is generally carried out when the distance is short or pipeline transportation is not convenient. Therefore, when transporting, it is necessary to select the appropriate method based on the geographical location and environment.

3.1. Carbon Storages Technology

The transported carbon dioxide is not only directly or indirectly utilized, but also a portion of it is stored. Traditional technologies for carbon dioxide storage can be roughly divided into geological storage, Marine storage, mineral carbonization and biological storage [14]. The purpose of doing so is not only to reduce the content of carbon dioxide, but also to facilitate subsequent utilization. Geological sequestration refers to the deep storage of carbon dioxide in suitable underground geological conditions, such as saline aquifers and unmined coal mine layers. This is also the most commonly used method at present [15]. Storing carbon dioxide deep in these geological layers can prevent it from being extracted and accidentally released back into the atmosphere, thus playing a role in sequestration. Therefore, only by choosing the right location can carbon dioxide be stored. If there is an unsuitable place, it may cause carbon dioxide to enter the atmosphere or react with other substances, thereby triggering earthquakes [15]. Places with porous rocks become a good choice because the voids in these rocks contain a relatively high concentration of salt water, just like a sponge before absorbing water [16]. Carbon dioxide can be absorbed and stored. With the maturation of technology and the previous experience in dealing with oil and gas, the risks have been greatly

reduced. According to what Wang Yonghong said in an interview, China is currently using underground projects such as non-ferrous metal mines and has proposed the idea of converting carbon dioxide into liquid for storage [17]. This way not only can most commercial demands be met, but also the sequestered carbon dioxide can be reused.

Marine sequestration refers to the process of storing carbon dioxide by taking advantage of its property that it can dissolve in water or form hydrates. The ocean makes up the largest proportion of the Earth apart from land. Therefore, this storage technology has received extensive attention. If feasible, the ocean will become the world's largest storage pool of carbon dioxide and contribute to global carbon dioxide activities. At present, the more popular form is to directly inject carbon dioxide gas into the deep sea and store it under the water column of the ocean through its different forms [18]. In addition, carbon dioxide can be injected into the relatively thick sedimentary layers located on the seabed. As there are voids in the sedimentary layers, it can be stored within them. Another idea is to utilize the ecological environment of the ocean to store carbon dioxide. Although these are still under research, as some studies have shown that excessive carbon dioxide may affect the Marine environment, such as causing acidification of seawater.

Mineral sequestration mainly utilizes the principle of mineral carbonization. That is, during the storage process, when carbon dioxide reacts with some natural minerals such as iron, magnesium and calcium, since these minerals are not only in large quantities but also relatively stable due to their long existence time, carbon dioxide will not be re-released into the atmosphere [19]. But even under normal conditions, these reactions still take a very long time to materialize. If one wants to accelerate the reaction, very strict conditions are required, such as whether the temperature and pressure have risen to the ideal level.

Biological sequestration, as the name suggests, is a type of sequestration method that utilizes natural means to store carbon dioxide. During their growth, plants can absorb carbon dioxide through photosynthesis, thereby storing it in the soil [20]. But at present, such means are just a conjecture.

3.2. Chemical utilization

The utilization in chemistry mainly relies on the chemical reactions between carbon dioxide and other substances to form synthetic materials. For instance, the obtained carbon dioxide can be used to synthesize methanol and carbonates for industrial applications, or to produce fuel. All these can contribute to the generation of solar energy [21]. Besides, carbon dioxide also has significant uses in the food industry. For example, it can be used as dry ice or refrigerant, which means that carbon dioxide can provide rapid freezing during food transportation. Or the function of maintaining a low temperature. Moreover, carbon dioxide has a special property, which is that it is not easy to react with other substances. This means that it can prevent the oxidation of products and protect the products from being damaged during the production process.

3.3. bio-utilization

Regarding bio utilization, in agriculture, when processing grains, carbon dioxide can be introduced into grain storage devices to kill insects that are harmful to agricultural products [22]. In addition, since plants need to carry out photosynthesis, emitting an appropriate amount of carbon dioxide in greenhouses where crops are grown can also help the growth of crops. In addition, carbon dioxide can be combined with other bio utilization technologies. For instance, the carbon dioxide from mobile phones can be used in collaboration with blue-green algae cell factories to produce biodegradable plastics. This not only solves the problem of global warming but also helps to clean the Earth's environment. In addition, there are studies that have achieved the synthesis of starch from carbon dioxide.

3.4. Geological utilization

As mentioned earlier, among the storage methods of carbon dioxide, there is a category known as geological storage. Since carbon dioxide is injected underground, it can react with underground

minerals, thereby generating fossil fuels [23]. Carbon dioxide can also play different roles in various geological conditions. In dry oil reservoirs, it can enhance the technology of oil extraction, and likewise in dry natural gas reserves, it can also strengthen the technology of natural gas extraction.

4. The Challenges of CCUS Technology

Although CCUS has many advantages and profound research value, due to technical reasons or not being fully developed, CCUS still faces multiple challenges and resistances. In terms of economy, CCUS is undoubtedly a project with considerable investment costs, with basic amounts ranging from tens of millions to hundreds of millions of yuan [24]. Moreover, problems may arise during operation, leading to additional costs. Therefore, sometimes enterprises may face difficulties in making choices. In terms of technology, as mentioned earlier, CCUS technology mainly involves several steps: capture, transportation, utilization and storage. During the discussion, it can be found that all these steps are very important. If any one of them fails, it will cause carbon dioxide to return to the atmosphere, thus leading to failure. However, the current technology can only reduce risks and minimize losses, which are still considerable. Due to the particularity of carbon dioxide, its utilization is very difficult as it requires the use of specific substances and also takes a considerable amount of time [24]. Enterprises need to invest a great deal of energy and money to complete these steps. This has led to the fact that most enterprises are reluctant to take the risk of investing a large amount of money in researching CCUS and trying out the feasibility of each method. Currently, the market size is not very large. The original intention of CCUS technology is to solve environmental problems. However, during the processing, it may also exacerbate environmental issues. For instance, in the process of carbon dioxide storage, if there is a leakage, it may lead to earthquakes or trigger other natural disasters, thereby affecting the activities of other organisms. All these indicate that CCUS technology is a technology with relatively high risks but also high benefits.

5. Conclusion

At present, the whole world is caught up in the goal of reducing carbon dioxide emissions. Therefore, compared with other technologies, CCUS is the most promising measure to achieve this goal, and the return to society will be of high value. Because CCUS not only can reduce carbon dioxide emissions but also can combine carbon dioxide with other energy sources or other substances, thereby promoting innovation and reform in research. This article briefly introduces and summarizes the process of CCUS technology, how the main steps are carried out, why they are done, and how to utilize CCUS technology. The author believes that if the goals of the Paris Agreement are to be achieved as soon as possible, one cannot rely solely on a single technology. Instead, the innovative value of CCUS technology should be fully utilized to enhance its commercial value, thereby promoting economic development and preventing the economy from being the main issue. In addition, during the use of carbon dioxide, thorough investigations should be conducted to minimize risk losses. Through comparison and research, the method with the least loss should be selected, and bases or experimental facilities should be built in a concentrated manner to reduce costs.

References

[1] Wang Jing, Gong Yuyang, Song Weining, Yang Pingjian The current development status and application prospects of CCUS technology, 2021.11.24, 2025.9.7, https://sisd.org.cn/express/shownews.php?id=598

[2] Amanda McGrath, Alexandra Jonker, What is carbon capture and storage (CCS)? 2024.5.13, 2025.9.7, https://www.ibm.com/cn-zh/think/topics/carbon-capture-storage

[3] Global Carbon Budget Carbon dioxide emissions from fossil fuels will increase again in 2024, 2024.11.13, 2025.9.7, https://globalcarbonbudget.org/fossil-fuel-co2-emissions-increase-again-in-2024/

[4] Gidden, M.J., Joshi, S., Armitage, J.J. et al. A prudent planetary limit for geologic carbon storage. Nature 645, 124–132 (2025).

[5] Liu E, Lu X, Wang D. A Systematic Review of Carbon Capture, Utilization and Storage: Status, Progress and Challenges. *Energies*. 2023, 16(6):2865.

[6] Yao J, Han H, Yang Y, Song Y, Li G. A Review of Recent Progress of Carbon Capture, Utilization, and Storage (CCUS) in China. *Applied Sciences*. 2023, 13(2):1169.

[7] Shan, Y., Guan, D., Zheng, H., Ou, J., Li, Y., Meng, J., Mi, Z., Liu, Z., Zhang, Q. China CO2 emission accounts 1997–2015. Sci. Data 2018, 5: 1–14.

[8] Nerem, R.S., Beckley, B.D., Fasullo, J.T., Hamlington, B.D., Masters, D., Mitchum, G.T. Climate-change–driven accelerated sea-level rise detected in the altimeter era. Proc. Natl. Acad. Sci. USA 2018, 115: 2022–2025.

[9] Kulp, S.A., Strauss, B.H. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat. Commun. 2019, 10: 1–12.

[10] Ogawa, F., Keenlyside, N., Gao, Y., Koenigk, T., Yang, S., Suo, L., Wang, T., Gastineau, G., Nakamura, T., Cheung, H.N., et al. Evaluating impacts of recent Arctic sea ice loss on the northern hemisphere winter climate change. Geophys. Res. Lett. 2018, 45: 3255–3263.

[11] Ouyang, Z., Qi, D., Chen, L., Takahashi, T., Zhong, W., DeGrandpre, M.D., Chen, B., Gao, Z., Nishino, S., Murata, A., et al. Sea-ice loss amplifies summertime decadal CO2 increase in the western Arctic Ocean. Nat. Clim. Change 2020, 10: 678–684.

[12] Rignot, E. Sea level rise from melting glaciers and ice sheets caused by climate warming above pre-industrial levels. Phys. –Uspekhi 2022, 65: 1.

[13] Hock, R., Huss, M. Glaciers and climate change. Climate Change, 3rd ed., Elsevier: Amsterdam, The Netherlands, 2021, 157–176.

[14] Stillman, J.H. Heat waves, the new normal: Summertime temperature extremes will impact animals, ecosystems, and human communities. Physiology 2019, 34: 86–100.

[15] Dosio, A., Mentaschi, L., Fischer, E.M., Wyser, K. Extreme heat waves under 1.5 C and 2 C global warming. Environ. Res. Lett. 2018, 13, 054006.

[16] Doak, D.F., Morris, W.F. Demographic compensation and tipping points in climate-induced range shifts. Nature 2010, 467: 959–962.

[17] Spence, A.R., Tingley, M.W. The challenge of novel abiotic conditions for species undergoing climate-induced range shifts. Ecography 2020, 43: 1571–1590.

[18] Seersholm, F.V., Werndly, D.J., Grealy, A., Johnson, T., Keenan Early, E.M., Lundelius, E.L., Winsborough, B., Farr, G.E., Toomey, R., Hansen, A.J., et al. Rapid range shifts and megafaunal extinctions associated with late Pleistocene climate change. Nat. Commun. 2020, 11, 1–10.

[19] Liu, Z., Deng, Z., He, G., Wang, H., Zhang, X., Lin, J., Qi, Y., Liang, X. Challenges and opportunities for carbon neutrality in China. Nat. Rev. Earth Environ. 2022, 3: 141–155.

[20] Sun, X., Zhang, H., Ahmad, M., Xue, C. Analysis of influencing factors of carbon emissions in resource-based cities in the Yellow River basin under carbon neutrality target. Environ. Sci. Pollut. Res. 2022, 29, 23847–23860.

[21] Xia, L., Wei, J., Wang, R., Chen, L., Zhang, Y., Yang, Z. Exploring Potential Ways to Reduce the Carbon Emission Gap in an Urban Metabolic System: A Network Perspective. Int. J. Environ. Res. Public Health 2022, 19, 5793.

[22] Zhao, X., Ma, X., Chen, B., Shang, Y., Song, M. Challenges toward carbon neutrality in China: Strategies and countermeasures. Resour. Conserv. Recycl. 2022, 176, 105959.

[23] Sarkodie, S.A., Strezov, V. Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries. Sci. Total Environ. 2019, 646, 862–871.

[24] Figueroa, J.D., Fout, T., Plasynski, S., McIlvried, H., Srivastava, R.D. Advances in CO2 capture technology—The US Department of Energy's Carbon Sequestration Program. Int. J. Greenh. Gas Control 2008, 2, 9–20.