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The Current Situation and Future Development Trends of CCUS

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Abstract: In the context of rising global CO_2 content, Carbon Capture, Utilization and Storage (CCUS) has come into people's attention because it can effectively reduce atmospheric CO_2 content. CCUS is mainly divided into three steps: capture, utilization and storage. Researchers have developed corresponding technologies that can improve efficiency and reduce losses in each link, and mature demonstration projects have emerged. However, the current development of CCUS still faces many difficulties, such as the technology is not mature enough, the integration level is low, the investment cost is high, the relevant talent shortage, and the business model is not yet formed and unclear. However, researchers have proposed some feasible solutions. This paper focuses on the CCUS process, outstanding related technologies, and lists some demonstration projects. In addition, it also summarizes the problems and solutions facing the current development of CCUS. Finally, the future of CCUS is prospected.

Keywords: CCUS, Carbon Capture Technology, Carbon Emission Reduction

1. Introduction

In the current severe situation of global climate change, the sharp increase in CO_2 emissions has become a significant issue that cannot be ignored. The rise in the global CO_2 content has, first of all, led to an increasingly obvious trend of global warming. The increase in temperature has caused glaciers to melt and sea levels to rise, thus threatening the ecological environment and the lives of residents in coastal areas. In addition, the increase in CO_2 content has also had a negative impact on the ecosystem. High concentrations of CO_2 cause changes in the photosynthesis rate of plants, thereby affecting the balance of the ecosystem and biodiversity. Most importantly, the increase in CO_2 emissions can also cause damage to the human respiratory and cardiovascular systems.

For the sustainable development of the environment and human society, it is essential to find effective ways to reduce the CO_2 content in the atmosphere. Therefore, the Carbon Capture, Utilization and Storage (CCUS) technology has come into the spotlight. It helps to reduce the amount of carbon dioxide in the atmosphere, enabling the permanent reduction of CO_2 emissions and contributing to combating climate change. Meanwhile, the captured high - purity carbon dioxide can be utilized as a raw material, for example, in industries and chemistry, creating new market opportunities and value chains. It can also improve oil and gas recovery rates and is expected to become a major technical means to support carbon recycling in the future.

The technical principle of CCUS mainly consists of three parts: The first one is capture include chemical absorption, membrane separation, pressure swing/temperature swing adsorption, etc.

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Among them, chemical absorption technology is the most commonly used. Secondly, storage. Storing the captured carbon dioxide underground or in other places is called carbon sequestration. This technology mainly includes underground sequestration and ocean sequestration. Thirdly, utilization. Converting the captured carbon dioxide into useful chemicals or fuels is called carbon utilization. Carbon utilization technologies mainly include chemical synthesis, biological synthesis, and electrochemical synthesis, etc. [1].

At present, major countries around the world are supporting the development of CCUS both domestically and globally. Countries in North America and Europe have relevant industrial policy support and implement measures such as subsidies and tax relief [2]. In China, there are already over 120 CCUS projects. Among them, CNPC, Sinopec and CNOOC have carried out CO_2 flooding field experiments in various types of oil reservoirs and achieved good results [3].

While CCUS is being vigorously developed globally, some related problems have emerged and corresponding solutions urgently need to be explored. For example, the technology is not mature enough, with low integration levels, the investment cost is extremely high, there is a shortage of relevant talents, and the business model has not taken shape and is unclear. All these issues will become constraints and obstacles to the further role - playing of CCUS in carbon reduction and carbon utilization [4].

This paper will briefly describe the principle and working process of CCUS technology and put forward certain solutions to the existing problems.

2. Working Process and Principles of CCUS

2.1. Principles of CCUS

CCUS, namely Carbon Capture, Utilization and Storage, mainly operates on the principle of separating carbon dioxide generated from industrial emissions or energy utilization, and then either directly utilizing it or injecting it into the strata to achieve permanent carbon dioxide emission reduction.

Specifically, the CCUS technology encompasses four main links as carbon dioxide capture, transportation, utilization, and storage.

2.1.1. Capture

Carbon dioxide is captured from industrial production or energy utilization processes. Depending on the capture method and the integration method with the energy system, it can be classified into precombustion capture, post combustion capture, oxyfuel combustion, and chemical looping combustion. According to different capture principles, it can be divided into solution absorption method, solid adsorption method, membrane separation method, cryogenic distillation method, etc.

2.1.2. Utilization

Convert carbon dioxide into valuable resources or products, such as preparing chemicals through chemical conversion, mineralization utilization, biological utilization, etc. This can not only reduce carbon dioxide emissions but also generate economic benefits.

2.1.3. Storage

Inject carbon dioxide into suitable strata, achieving long - term isolation from the atmosphere through geological processes. Storage sites usually include depleted oil and gas reservoirs, deep saline aquifers, etc.

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2.2. Working Process of CCUS

Based on the understanding of the principles of CCUS, we will now explore its specific working process in practical applications.

2.2.1. Capture

First, gases containing carbon dioxide, such as flue gas emitted from industries [5], will undergo pretreatment, such as desulfurization, denitrification, and dust removal, to remove other impurities and ensure the efficiency of the subsequent capture process.

The capture process varies according to specific technical types. Taking the chemical absorption method [5] as an example, the pretreated gas will enter the absorption tower and come into counter - current contact with the absorption liquid (such as amine solution) sprayed from the top of the tower. Here, carbon dioxide will react chemically with the absorption liquid and be absorbed into the liquid, forming a rich liquid. The rich liquid is then transported to the desorption tower, where the reaction is reversed by heating, releasing carbon dioxide, thus achieving the separation and recovery of carbon dioxide.

For other technologies, such as the physical absorption method, adsorption method, membrane separation method, and cryogenic separation method [5], their working processes also have their own characteristics. For instance, the physical absorption method uses organic solvents to absorb acidic gases under pressure, and the regeneration of the solvent is achieved by depressurization. The adsorption method selectively adsorbs carbon dioxide by an adsorbent under certain conditions and then desorbs it to achieve separation. The membrane separation method separates gases based on the different permeability of specific membranes to different gases. The cryogenic separation method liquefies gases by pressurizing and cooling, thereby achieving the separation of carbon dioxide.

After capturing carbon dioxide, it usually needs to be compressed and purified to meet the requirements of subsequent utilization or storage.

2.2.2. Storage

Carbon dioxide storage is a crucial process to ensure that carbon dioxide is safely and effectively stored to prevent it from leaking back into the atmosphere and causing secondary pollution.

For geological storage, depleted oil and gas fields, deep saline aquifers, etc. are usually selected as storage sites. These sites are required to have good sealing properties and large storage capacities, enabling them to hold carbon dioxide stably for a long time. Marine storage requires the selection of suitable deep - sea areas and must be carried out under strict environmental monitoring.

For geological storage, geological exploration is carried out first. Through geological exploration, a suitable injection layer is determined, which usually involves a detailed analysis of underground rock formations, including the permeability, sealing property, and depth of the rock formations. Then, the construction of injection wells is carried out. Injection wells are built at the selected injection points, which usually include steps such as drilling, well completion, and the construction of wellhead facilities. After completing the above processes, carbon dioxide can be injected into the selected geological structure. During the injection process, the injection pressure and injection rate need to be strictly controlled to ensure that carbon dioxide can be evenly distributed into the pores and fractures of underground rock formations. In the later stage, long - term monitoring and maintenance of the storage site are also required, including monitoring the stability of underground rock formations, the migration of carbon dioxide, and its possible impacts on groundwater and the surface environment. If any abnormal situations are detected, measures need to be taken promptly.

For marine storage, suitable deep - sea areas are selected as storage sites according to factors such as the marine environment and geological conditions. Carbon dioxide is injected into the deep sea

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under strict environmental monitoring. This usually involves converting carbon dioxide into a liquid or supercritical state, and then injecting it into the seabed strata or water bodies through pipelines or specially designed injection devices. After injection, long - term environmental monitoring of the storage area is required, including monitoring the carbon dioxide concentration in seawater and changes in the marine ecosystem. If any adverse impacts on the marine ecosystem are detected, measures need to be taken promptly.

The carbon dioxide storage workflow is a complex and sophisticated systems engineering that requires comprehensive consideration of multiple factors such as geological conditions, technical feasibility, economic costs, and environmental impacts.

2.2.3. Utilization

The utilization of carbon dioxide is a crucial step in converting the captured carbon dioxide into valuable resources or products.

Based on the properties of carbon dioxide and market demands, appropriate utilization methods are selected. There are various ways to utilize carbon dioxide.

The first way is physical example, it is used as a fire extinguishing agent, an additive in carbonated beverages, and in dry ice production. These utilization methods are relatively simple, but the added value is secondly way is chemical engineering utilization: Through chemical conversion, carbon dioxide is transformed into high - value - added chemicals, such as methanol, urea, and organic polymer materials. These utilization methods require a high level of technology and cost investment, but they have high economic value and environmental utilization is also a good method. Using organisms like microalgae to convert carbon dioxide into food, feed additives, or bio-energy. This utilization method is environmentally friendly and sustainable, but it is still in the research and development, but not least, geological utilization is an important aspect in approach to reach the as enhanced oil recovery (injecting carbon dioxide to increase the fluidity of crude oil and improve the recovery rate). This utilization method can not only achieve carbon dioxide emission reduction but also improve energy utilization efficiency.

Throughout the utilization process, it is necessary to monitor and evaluate the conversion efficiency of carbon dioxide, product quality, and environmental impact. This helps to identify problems in a timely manner and take measures for improvement and optimization.

3. Technologies and Demonstration Projects

For each process step of CCUS, researchers have developed relevant application technologies that can improve work efficiency, reduce process losses, and better achieve the goals of each process stage. The following are two relatively mature CCUS negative - emission technologies and their related demonstration projects.

3.1. CO_2 Direct Air Capture (DAC)

The CO_2 Direct Air Capture (DAC) technology is an emerging carbon capture technology aimed at directly capturing carbon dioxide from the atmosphere for utilization or storage. This technology uses specific chemical substances (such as adsorbents or absorbents) to directly capture carbon dioxide from the air.

The DAC technology is mainly divided into two types: liquid - based DAC and solid - based DAC.

The first type is Liquid - based DAC. Air is passed through a chemical solution (such as a hydroxide solution) to remove carbon dioxide. Another type is Solid - based DAC: Solids that can chemically bind with carbon dioxide are used as absorbents. When heated under vacuum, they release concentrated carbon dioxide, which can be collected for subsequent storage or use.

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Currently, companies such as Climeworks in Switzerland and Carbon Engineering in Canada have been dedicated to the research of DAC technology for many years and have had several successfully - operated DAC projects [6].

Climeworks was founded in Switzerland in 2009. In 2014, Climeworks, in cooperation with Sunfire and Audi, established the first pilot plant, which could capture 80% of the CO_2 in the environment and convert it into synthetic diesel [7]. In 2017, Climeworks AG successfully operated the world's first industrial - scale direct air capture plant, capturing 900 tons of CO_2 annually. The captured CO_2 was directly transported to nearby greenhouses or the beverage industry. Since 2020, Climeworks has successively launched two direct air capture and storage projects, with annual CO_2 capture amounts of 4,000 tons and 36,000 tons respectively [8].

Carbon Engineering (CE) was founded in Canada in 2009 by Professor David Keith of Harvard University [9]. In 2017, CE, in cooperation with researchers from Harvard University, developed an industrial production method that can directly capture CO_2 from the air and use it to produce liquid fuels. In 2021, CE established a carbon engineering research and development center and created the world's largest DAC research facility. In 2022, CE, in cooperation with 1PointFive, completed the process design of the world's first one - million - ton large - scale commercial DAC project. It is expected that after the project is put into operation, it can capture 500,000 tons of CO_2 from the atmosphere annually and has the capacity to expand to 1 million tons per year [10].

3.2. Bio Energy with Carbon Capture and Storage (BECCS)

Bio Energy with Carbon Capture and Storage (BECCS) is a special category within the Carbon Capture, Utilization and Storage (CCUS) technology. The BECCS technology integrates the utilization of biomass energy with carbon capture and storage. It first harnesses the photosynthesis of plants to convert CO_2 in the atmosphere into organic matter, which is accumulated and stored in the form of biomass. This biomass can either be directly burned to generate heat or synthesized into other high - value clean energy through chemical reactions. The CO_2 released during the combustion and chemical synthesis of biomass is regarded as the release of the CO_2 stored during plant growth (this process is part of "net - zero emissions"). Subsequently, CCS technology is employed to capture the released CO_2. After further compression and cooling, the CO_2 is transported by ships or pipelines and finally injected into suitable geological structures for permanent storage (this process is "negative emissions"). The advantage of this technology lies in the renewable nature of its resources. Biomass, as a renewable energy source, is widely distributed and has diverse origins, which gives the BECCS technology significant development potential.

Currently, there are around 20 BECCS facilities and demonstration projects at various stages globally, mainly located in North America, Europe, and Japan. They are applied in areas such as bio - ethanol production, bio - oil production, biogas production, biomass gasification, and biomass power generation. The captured CO_2 is entirely used for enhanced oil recovery (EOR), the food and beverage industry, manufacturing, or geological storage. The majority of BECCS projects are concentrated in the ethanol production industry in North America. As of 2022, there were 192 operational bio - ethanol plants in the United States. Projections indicate that if all these bio - ethanol plants were to deploy BECCS technology, approximately 45 million tons of CO_2 could be removed from the atmosphere annually.

Currently, the world's largest BECCS project is the Illinois Industrial Carbon Capture Project (ILCCS) in the United States. High - purity wet CO_2 generated during the corn - fermentation process for ethanol production is transported by blowers to a reciprocating compressor equipped with coolers and separators. Then, a dehydration unit is used to reduce the water content of the compressed CO_2. Finally, the liquid CO_2 is transported and injected into a nearby sandstone saline aquifer for storage.

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This project started injecting the captured CO_2 in 2017. Compared with other CCS technologies, its cost is relatively low [11].

Drax was once the largest coal - fired power plant in Western Europe with the highest carbon emissions. Currently, it has become one of the power generation projects in Europe with the lowest carbon emission intensity.

Drax has demonstrated the world's first BECCS demonstration project near Selby, North Yorkshire. It achieved the first capture of CO_2 from the flue gas released by a power plant using pure biomass as raw material. This project adopted a special absorption solvent developed by C - Capture at the University of Leeds. During the one - day trial operation of the project, 1 ton of CO_2 was captured. Currently, Drax Power Station is deploying large - scale BECCS. It is expected that by 2027, Drax may become the world's first carbon - negative power station [12].

4. Problems and Possible Solutions in the Current Development of CCUS

4.1. Problems

As mentioned above, the CCUS technology is not yet mature enough [3], with low integration [5], high investment costs [3], a shortage of relevant talents, and an unformed and unclear business model.

The CCUS technology is not mature enough. Some key technologies have not reached the level of commercial application, and there is a lack of unified technical standards and specifications. The infrastructure is incomplete. For example, the construction of infrastructure such as pipeline layout and storage sites are still imperfect, which restricts the large-scale application of CCUS technology. In addition, the investment cost of CCUS is indeed high, which is mainly caused by factors such as its technical complexity, infrastructure construction requirements, and energy consumption during operation. The shortage of talents mainly stems from the complexity and novelty of CCUS technology and the high requirements for professional knowledge and skills in this field. It involves multiple disciplines, including chemistry, physics, geology, engineering, etc., and requires professionals with interdisciplinary knowledge and practical experience. At present, such talents are relatively scarce globally. Even if there are graduates in related majors, their skills may not match the actual needs of CCUS technology. This may be because the education system has not yet fully adapted to the development of this emerging field, or because graduates lack sufficient practical experience. Moreover, since the CCUS technology is a relatively emerging field, there are relatively few experts with rich experience. Due to its novelty, commercialization has not been fully formed. Most projects have limited and unstable profitability, the profit model is not clear, and there is a lack of a sustainable business model.

All of the above are restricting the development and promotion of CCUS, and these problems need to be solved urgently.

4.2. Possible Solutions

To address the issues of low integration and high investment costs, it is recommended that researchers intensify their efforts in researching and developing key technologies to improve technological maturity, providing solid technical support for system integration. They should also formulate unified technical standards and specifications to reduce unnecessary investment waste, improve the utilization rate and efficiency of infrastructure, and complete the infrastructure construction. Speeding up the construction of infrastructure such as pipeline layout and storage sites can provide a strong guarantee for the large - scale application of CCUS technology, and the unit cost can be reduced through economies of scale.

To bridge the talent gap, there is an urgent need to strengthen education and training to cultivate more professionals with interdisciplinary knowledge and practical experience. Meanwhile,

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cooperation with relevant enterprises can be carried out to launch internship and practical training programs, enhancing students' practical abilities and employment competitiveness. Promoting industry - university - research cooperation can also be beneficial, facilitating close collaboration among academia, industry, and research institutions. Through joint research and development projects, sharing of resources and achievements, the innovation and application of CCUS technology can be advanced.

To accelerate the establishment of a commercial model for CCUS, it can be achieved by exploring diversified sources of revenue. For example, developing CCUS emission reduction trading, expanding carbon utilization methods, and providing additional services such as consulting or technical services to increase sources of income. At the same time, policy support and incentives should be strengthened. The government can introduce clearer and more specific support policies and incentive mechanisms, such as providing loans, subsidies, and tax incentives [5]. Moreover, promoting cluster construction and large - scale application can be carried out by advancing large - scale, full - chain demonstration projects in suitable areas.

5. Conclusion

This paper comprehensively analyzed the latest progress in the field of CCUS technology, introduces its working process, lists some CCUS technologies and demonstration projects, and analyzes the application status and challenges. These challenges not only restrict the further development of this field but also have a profound impact on the global progress of carbon emission reduction and environmental governance. The solutions include technological research and development, improvement of infrastructure, promotion of the integration of academia, industry, and scientific research, and strengthening of policy support and encouragement. In conclusion, CCUS has broad development prospects, but still needs to overcome many challenges. Future research will continue to deepen the understanding of CCUS, explore its practical applications, and address potential challenges, making greater contributions to promoting its development.

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