PROCEEDINGS OF THE
INTERNATIONAL CARBON NEUTRALITY TRAINEESHIP PROGRAM
Volume.02, Number.1, 2024, 17-24

Carbon Capture and Storage Technologies: Current Advancements and Future Potential

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Abstract

With the growth of the global economy and the expansion of industrial activities, greenhouse gas emissions have become one of the main causes of global warming and climate change. Carbon dioxide is one of the most common greenhouse gases, and the increase in its emissions leads to irreversible impacts such as global warming and sea level rise. Therefore, reducing carbon dioxide emissions is an urgent task in addressing climate change. Carbon capture and storage (CCS) technology is a key technology aimed at reducing greenhouse gas emissions and achieving carbon neutrality. This technology captures carbon dioxide generated during industrial processes and stores it in underground storage to prevent its release into the atmosphere. This article will cover four parts: introduction to CCS technology, research methods, research results, and discussion of results. This article mainly introduces the specific content and challenges of CCS technology, and proposes solutions based on one's own understanding. With the development of society and technological progress, CCS technology will continue to improve and progress, and its influence will also increase.

Keywords: Global warming; greenhouse gases; carbon capture and storage; carbon neutrality.

1. Carbon capture and storage technologies: current advancements and future potential

Global carbon emission is now becoming an urgent global climate issue. The main purpose of "Paris Agreement" is to control the global average temperature increment less than 2°C in comparison to the pre-industrial (Zhao Rui,Zhang Yi,Zhang Shuai,Li Yan,Han Tao & Gao Li, 2021). Carbon capture and storage (CCS) technology research has been ongoing for several years with the aim of mitigating greenhouse gas emissions and addressing climate change and it is an emerging technology to promote global carbon neutrality. While the technology shows promise, there are still significant challenges that need to be overcome.

Firstly, for carbon capture technology, CCS involves capturing carbon dioxide (CO_2) emissions from power plants and industrial facilities before they are released into the atmosphere (Wang Rutian,Wen Xiangyun,Wang

Xiuyun,Fu Yanbo & Zhang Yu, 2022). Various capture technologies have been explored, including post-combustion capture, pre-combustion capture, and oxy-fuel combustion. Post-combustion capture, which involves capturing CO_2 from flue gases, is the most mature and widely deployed technology. Secondly, in terms of carbon storage (Yang Yinan,Li Jing,Wang Li,Wang Zihao,Ling Yun,Xu Jialong... & Zhao Lixia, 2022) and utilization, Once captured, the CO_2 needs to be stored or utilized to prevent its release into the atmosphere. The most common method of storage is geological storage, where CO_2 is injected into deep underground formations such as depleted oil and gas reservoirs or saline aquifers (He Zhili,Lin Lu,Wang Xin,Qin Wei & Zhang Chuanlun, 2022). Research has focused on assessing the long-term storage capacity and potential leakage risks associated with geological storage. Additionally, efforts have been made to explore the utilization of CO_2 in enhanced oil recovery (EOR) and the production of building materials or fuels. Thirdly, Monitoring and verification techniques are crucial to ensure the integrity of stored CO_2 and to detect any potential leaks. Research has been conducted to develop reliable monitoring technologies, including geophysical methods, geochemical monitoring, and remote sensing techniques. These monitoring techniques help assess the behavior of CO_2 over time and provide early warning of any leakage. Fourthly, regarding the cost and energy consumption of CCS technology, one of the major challenges of CCS technology is its cost and energy requirements. Capturing, transporting, and storing CO_2 can be energy-intensive and expensive. Research efforts have focused on improving the efficiency and cost-effectiveness of capture technologies, as well as optimizing transportation and storage infrastructure. Technological advancements and scale-up of CCS projects are expected to drive cost reductions in the future. Finally, the development and deployment of CCS technology require supportive policy and regulatory frameworks. Governments and international organizations have been working to establish regulations, financial incentives, and carbon pricing mechanisms to encourage CCS deployment. Research has examined the effectiveness of these policies and identified ways to enhance their implementation and coordination across regions (Matthew Billson & Mohamed Pourkashanian, 2017). Overall, CCS technology research has made significant progress in understanding the technical aspects of capturing, storing, and utilizing CO_2. However, challenges such as high costs, energy requirements, and public acceptance remain (Subraveti Sai Gokul,Rodríguez Angel Elda,Ramírez Andrea & Roussanaly Simon, 2023). Continued research, development, and large-scale demonstration projects are crucial for improving the efficiency, affordability, and scalability of CCS technology to play a significant role in reducing greenhouse gas emissions and addressing climate change.

The structure of this article mainly consists of three parts: methods, results, and discussion. Firstly, in the method section, introduce the search strategy for CCS technology and the main research directions that will be introduced (most of which are popular technologies). In the result part, after reading a lot of relevant articles, I found my understanding of CCS technology (mainly the basic principles) and the importance of CCS technology to carbon neutrality. In addition, identify the shortcomings of existing CCS technology, as well as the challenges and opportunities it brings. In the discussion section, we mainly formulate and propose suggestions on how to address the aforementioned shortcomings and challenges, and provide suggestions for future research.

2. Method

2.1. Search strategy

Start with general search terms, for example: Carbon capture and storage technology, CCS technology research, Feasibility of CCS technology, Source standards for carbon capture and so on. Then, use more specific terms to narrow down the search scope: advanced capture technologies for CCS, techno-economic analysis of CCS projects, public acceptance of CCS technology, policy and regulatory frameworks for CCS, geological storage of CO2, Carbon capture from industrial processes, monitoring and verification techniques for CCS, life cycle assessment of CCS technology. In addition, there are some useful exploration academic databases and research platforms: Google Scholar (scholar.google.com), IEEE Xplore (ieeexplore.ieee.org), ScienceDirect (www.sciencedirect.com), ResearchGate (www.researchgate.net), ACM Digital Library (dl.acm.org), SpringerLink (link.springer.com). Finally, review relevant scientific articles, research papers, and conference proceedings and consult reports and publications from international organizations and governmental bodies. Such as look for recent publications (last 5-10 years) to ensure up-to-date information,pay attention to studies conducted by reputable research institutions, universities, and government agencies; check for review papers or meta-analyses that provide a comprehensive overview of CCS technology research and feasibility assessments.

2.2. Important technologies

Research on CCS technology is a dynamic field that continues to evolve as scientists and engineers strive to improve its effectiveness and overcome existing challenges. Here are some ongoing research areas and developments in CCS technology:

(1) Advanced capture technologies:

Researchers are exploring novel capture technologies to enhance efficiency and reduce energy requirements. This includes the development of advanced solvents and sorbents for post-combustion capture, as well as the investigation of new pre-combustion and oxy-fuel combustion processes. Additionally, research is being conducted on membrane-based separation technologies and solid sorbents that can offer cost-effective and energy-efficient capture solutions.

(2) Carbon capture from industrial processes:

Beyond power plants, research is expanding to capture CO_2 emissions from various industrial processes, such as cement production, steel manufacturing, and chemical production. These sectors contribute significantly to global emissions, and developing effective capture technologies for these industries is a focus of on going research. Strategies include optimizing process integration, exploring alternative feedstocks, and implementing tailored capture approaches.

(3) CO_2 storage and enhanced storage techniques:

Research is being conducted to better understand and optimize CO_2 storage methods. This includes studying the behavior of CO_2 in different geological formations, evaluating the potential for offshore storage, and improving the modeling of CO_2 behavior over the long term. Enhanced storage techniques, such as carbon mineralization (transforming CO_2 into stable mineral forms) and injecting CO_2 into deep saline formations, are also being investigated for their feasibility and long-term stability.

(4) Monitoring, verification, and risk assessment:

Efforts are underway to enhance monitoring and verification techniques to ensure the integrity of CO_2 storage sites and detect potential leaks. This involves the development of advanced monitoring tools, such as distributed sensor networks, satellite-based monitoring, and real-time data analysis. Risk assessment methodologies are also being refined to evaluate the environmental and social impacts of CCS projects and develop robust regulatory frameworks.

(5) Integration with renewable energy systems:

Researchers are exploring the integration of CCS with renewable energy systems, such as bioenergy with carbon capture and storage (BECCS). BECCS involves capturing CO_2 emissions from biomass combustion and storing it underground, resulting in negative emissions. The synergistic use of renewable energy and CCS can help decarbonize multiple sectors and contribute to achieving climate targets.

(6) Life cycle assessment and techno-economic analysis:

Comprehensive life cycle assessments and techno-economic analyses are being conducted to evaluate the overall environmental and economic viability of CCS technology. These assessments consider the entire CCS chain, from capture to storage, and assess factors such as energy consumption, cost, environmental impacts, and potential benefits.

(7) Public acceptance and policy research:

Understanding public perceptions, concerns, and acceptance of CCS technology is an important area of research. Studies are being conducted to identify barriers to public acceptance, assess the social and cultural dimensions of CCS deployment, and develop effective communication strategies. Policy research focuses on designing supportive frameworks, evaluating financial mechanisms, and exploring international collaborations for the deployment of CCS technology.

3.Results

3.1. Basic principles

CCS stands for carbon capture and storage, which is a technology aimed at reducing carbon dioxide emissions from industrial processes and power generation by capturing carbon dioxide and storing it underground or for other purposes. The basic principles of CCS include three main steps: capture, transportation, and storage.

Firstly, carbon capture: The first step of CCS is to capture carbon dioxide emissions from large point sources such as power plants, cement plants, or industrial facilities. There are different CO_2 capture methods, such as post combustion capture, which includes capturing CO_2 from the flue gas after the combustion process. It usually uses chemical solvents or adsorbents to separate CO_2 from other gases. For pre combustion capture, in this method, carbon capture is carried out before fuel combustion. The fuel is converted into a mixture of hydrogen and CO_2, and CO_2 is separated from the hydrogen for storage. There is also oxygen fuel combustion, which involves burning fuel with pure oxygen instead of air, producing smoke mainly composed of carbon dioxide and water vapor. Then CO_2 can be captured from the flue gas. Next is carbon transportation, once carbon dioxide is captured, it needs to be transported to suitable storage locations. Typically, pipelines are used to transport CO_2 from capture facilities to storage locations. These pipelines are similar to those used for natural gas transportation, but due to the nature of carbon dioxide, they may require additional safety measures. The last is carbon storage. The captured carbon dioxide is stored in the tectonics deep underground to prevent it from entering the atmosphere. The most common storage method is geological storage, which includes injecting carbon dioxide deep underground, such as depleted oil and gas reservoirs, aquifers, or nonexploitable coal seams. A better way to utilize CO_2 is to increase oil recovery rate (EOR), which not only generates economic benefits but also permanently stores CO_2. According to research, the potential for CO_2 flooding is enormous, with 13 billion tons of crude oil stored in geological structures suitable for CO_2 flooding, which can simultaneously store approximately 5-6 billion tons of CO_2 during oil displacement. This shows that there is a great potential for the development and utilization of CO_2 through EOR, which provides a prerequisite for promoting carbon capture and storage in the world through market driving.

Carbon dioxide is trapped in these formations for a long time, reducing the risk of release into the atmosphere. CCS technology is still being developed and implemented on a large scale. Although it has the potential to significantly reduce carbon dioxide emissions, there are also some challenges that need to be overcome, such as implementation costs, ensuring safe storage, and monitoring potential leaks.

In addition, research is currently underway to explore alternative methods such as direct air capture (DAC), which aims to directly capture carbon dioxide from the ambient air.

3.2. Application examples

CCS (Carbon Capture and Storage) technology is a key technology for addressing climate change, used to reduce greenhouse gas emissions such as carbon dioxide (CO_2) and store them to prevent their release into the atmosphere. Give a few practical examples of CCS technology application: coal-fired power plants: CCS technology can be applied to coal-fired power plants by capturing and separating CO_2 from flue gas, compressing it into a liquid or supercritical state, and storing it in underground reservoirs or other underground spaces to reduce CO_2 emissions in the atmosphere. Industrial production process: CCS technology can be applied to high carbon emission industrial production processes, such as steel, cement, chemicals, and petroleum refining industries. By capturing and storing the generated CO_2 in these factories, the negative impact of industrial processes on climate can be reduced. Natural gas processing plants: CCS technology can be used to capture and treat CO_2 generated during natural gas processing, in order to reduce greenhouse gas emissions. These captured CO_2 can be transported to storage sites through pipelines or reused for industrial purposes. Biomass energy power generation: CCS technology can be combined with biomass energy power generation to capture and store the CO_2 generated during the power generation process, thereby achieving net zero emissions. Biomass energy includes wood, crop waste, and other renewable biomass. Drilling and oil and gas extraction: CCS technology can also be applied to the oil and gas extraction industry. By capturing and storing CO_2 released during drilling and oil and gas production processes, greenhouse gas emissions can be reduced and energy sustainability can be improved. These are just some examples of the application of CCS technology, and there are other areas where CCS technology can also be used to reduce greenhouse gas emissions and reduce the impact on climate change. However, it should be noted that CCS technology is still constantly developing and improving, and there are still some challenges and cost issues in practical applications.

3.3. Existing problems and challenges

With the improvement of new energy power generation technology and the decrease in power generation technology costs, the development of CCS has been controversial. Some research institutions believe that CCS technology is generally expensive and cannot reach commercial scale. There are also serious practical problems with the transportation, injection, and storage of captured CO_2 after carbon capture. There are two basic operating modes to reduce CO_2 generated by coal combustion: one is to remove CO_2 before coal combustion; The second option is to choose the post combustion method to remove the flue gas before entering the atmosphere. There are three main technical options: pre combustion, post combustion, and enriched combustion. CCS technology is mainly concentrated in industries such as oil and gas production, fertilizers, and power generation. For example, in the North African region, the In Salah project can separate CO_2 from the natural gas produced and inject it back into the oil and gas reservoirs produced. Sleipner in Norway is the world's first fully operational offshore natural gas field capable of CO_2 injection. In the United States, Koch Nitrogen captures CO_2 generated during fertilizer production at its factory in Enid, Oklahoma, and then transports it to improve oil recovery rate (EOR).

CCS policy is mainly aimed at addressing climate change, but it is far from sufficient for investing in the development of CCS technology. In fact, without strong and sustainable policies, global investment in CCS cannot be sustained. In the context of ensuring global population growth and wealth growth, reducing greenhouse gas emissions will incur huge costs, and in the long run, the benefits are uncertain. The public usually does not weigh the gains and losses of CCS technology on their own, so global policies towards CCS must be sufficient to change the actions of all stakeholders. For example, it is widely believed that releasing CO_2 into the atmosphere is easier and cheaper than capturing permanently stored CO_2. The CCS capital market has not received sufficient returns to meet the required investment return rate. Unclear policies still pose significant challenges to the future development of CCS. A new project has emerged in CCS, and established business models, structures, and practices in mature industries will be applied to CCS projects. However, these aspects of CCS are not yet mature, and high risks lead to high investment returns. Therefore, CCS financing is also very difficult. In addition, CCS investment requires long-term capital asset investment. A single project can slow down millions of tons of CO_2 emissions annually, requiring an initial investment of billions or billions of dollars. After decades of operation, investors must have sufficient confidence to understand the current and future policy environment, effectively carry out projects, optimize risk investment strategies, and achieve positive financial investment decisions.

3.4. Importance for carbon neutrality

CCS (carbon capture and storage) technology is a key tool to achieve global carbon neutrality. Firstly, in terms of reducing carbon emissions, CCS technology helps to reduce carbon dioxide emissions from industrial processes and power generation, which is the main cause of global greenhouse gas emissions. CCS technology can help reduce emissions by up to 90% by capturing and storing carbon dioxide. Secondly, CCS technology supports renewable energy. CCS technology can support the growth of renewable energy sources such as wind and solar energy by providing a way to store excess energy. These stored energy can be used when renewable energy is not available, helping to balance the energy grid. It is worth noting that in promoting the development of carbon neutrality industries, CCS technology can help cement, steel and chemicals industries become carbon neutrality industries by capturing and storing carbon dioxide emissions. This is particularly important in industries where it is difficult to reduce emissions through other means. In addition, CCS technology can create new industries that focus on capturing and storing carbon dioxide. These industries can provide new employment and economic opportunities for regions affected by the decline of traditional industries. Finally, CCS technology is a key tool for achieving global climate goals, such as the Paris Agreement's goal of limiting global warming to below $_2$ degrees Celsius. Without CCS technology, achieving these goals and avoiding the most severe impacts of climate change will be even more difficult.

In short, CCS technology is a key tool to achieve global carbon neutrality. CCS technology can help pave the way for a more sustainable future by reducing emissions, supporting renewable energy, supporting carbon neutrality industries, creating new industries and supporting climate goals.

4. Discussions

4.1. This study found problems encountered by CCS technology

The first and most important and practical issue is high cost. The high cost of CCS technology is the main obstacle to its practical application. The high cost of CCS technology mainly includes the following aspects: firstly, the cost of carbon capture, which requires additional equipment and processes to separate and capture gases. The construction, operation, and maintenance of these equipment and processes require considerable investment, increasing the cost of industrial sites. Secondly, there is transportation cost, which also requires a certain cost to transport the captured carbon dioxide from industrial sites to underground storage locations. Special pipelines or transportation equipment are required during the transportation process, and the construction and maintenance of these equipment will also increase costs. Furthermore, the cost of storage requires the selection of suitable geological layers, sealing, and monitoring to safely store carbon dioxide in underground storage locations. These processes involve complex engineering and geological requirements, and the reliance on equipment and technology increases costs. Finally, there is the cost of monitoring and management, ensuring the safety of storage locations and monitoring emissions also requires a certain amount of cost investment. It is necessary to monitor the stability of underground storage points and the risk of carbon dioxide leakage to ensure the effectiveness of technology and environmental safety.

Secondly, CCS technology is in the development stage and is not yet mature, with many not yet fully validated. Although this technology is theoretically feasible and has some demonstration projects, there are still some challenges and limitations in practical application. Further research and testing are needed to ensure its safety and reliability. CCS technology requires the collaborative operation of various equipment, processes, and systems to capture, transport, and store carbon dioxide. At present, the maturity of these technologies is still improving, and more research and practice are needed to solve technical problems, improve efficiency and reliability. As mentioned earlier, the high cost of CCS technology remains a challenge for commercial applications. In practical applications, more research and innovation are needed to reduce costs and improve economic feasibility. In addition, permanently storing carbon dioxide underground requires selecting suitable geological layers and ensuring their safety and stability. More research is still needed on the feasibility of long-term storage and the monitoring and evaluation of geological layers. At present, CCS technology is mainly applied to a few demonstration projects and large industrial sites, but to achieve comprehensive benefits of carbon emissions reduction, it is necessary to promote and expand the technology on a broader scale. This involves more investment and infrastructure construction.

Although CCS technology has received extensive research and discussion in the academic and technological communities, it is not well-known to the general public. The first reason for the low public awareness is that CCS technology is relatively new and has a relatively short development history compared to traditional energy and environmental protection technologies. Therefore, there is relatively little public understanding and awareness of this technology. However, some governments lack publicity and education, and the promotion and education efforts of CCS technology are relatively low. The public's attention to climate change and environmental protection is mainly focused on renewable energy and energy efficiency, while CCS technology is often not sufficiently promoted and promoted, resulting in limited public understanding. In terms of cognition, CCS technology involves complex processes and scientific principles, and involves knowledge in many fields such as chemistry, engineering, geology, etc. For the general public, these technical content may be difficult to understand and accept. Moreover, CCS technology involves sensitive issues such as carbon emissions, energy development, and environmental protection, and there is some controversy. Some people hold a skeptical attitude towards the effectiveness and feasibility of CCS technology, which may also affect the public's understanding and acceptance of the technology.

4.2. Measures to address issues

In order to address the high cost of CCS technology and the urgency of promoting technological innovation, the following measures and methods can be taken: the government can formulate policies and regulations to support the development of CCS technology, and provide economic incentives, such as subsidies, tax incentives, and incentive mechanisms, to reduce the cost of technology and encourage relevant industries to adopt CCS technology. Increase investment in the research and innovation of CCS technology, including improving the efficiency of capture, transportation, and storage technologies, reducing equipment costs, and exploring new materials and methods to reduce overall costs. By promoting the scale and centralization of CCS projects, economies of scale and cost reduction can be achieved. In addition, cooperation and sharing of CCS facilities and infrastructure among multiple related industries can also reduce costs. Attracting public and private investment to provide financial support for the research and development, demonstration projects, and commercial deployment of CCS technology. Investors and financial institutions can participate in the investment and risk sharing of CCS projects, thereby reducing the cost of technology. International cooperation and knowledge sharing can accelerate the development and application of CCS technology, reduce duplicate efforts, and share experiences and lessons learned. Cooperation between international organizations, governments, and research institutions can reduce the cost of technology and accelerate its maturity. In addition, continuous monitoring and evaluation of CCS projects are carried out to promptly identify and address issues and risks. By optimizing and improving the project, technical efficiency can be improved and costs can be reduced. The implementation of these measures requires the joint efforts and support of the government, industry, academia, and society. With the advancement of technology and the utilization of scale effects, the cost of CCS technology is expected to gradually decrease, providing more opportunities for its widespread application. Encourage cooperation and exchanges between researchers and experts in different fields, including chemistry, engineering, geology, materials science and other fields. Cross disciplinary cooperation can promote the emergence of new ideas and innovative solutions. Some commercial institutions can organize innovation competitions and incentive mechanisms to encourage research institutions, enterprises, and individuals to propose innovative CCS technology solutions. By rewarding outstanding innovators, we can accelerate and break through technological innovation. International governments promote knowledge sharing and cooperation, including cooperation between academia, industry, and government, in the field of CCS technology. Conducting collaborative research projects, organizing international conferences and seminars, and other activities can promote knowledge exchange and technological innovation. Of course, academic training and talent reserve are also very important, strengthening academic training and talent reserve in the field of CCS technology. Support education and training in related majors, cultivate more professional talents and technical personnel, and provide strong support for technological innovation.

To increase public awareness of CCS technology, the following measures can be taken: to carry out education and publicity activities targeting the public, explaining the principles, applications, and potential benefits of CCS technology to them. Utilize various channels such as media, social media, websites, public lectures, etc. to convey information about CCS technology. Some research teams can showcase existing successful cases and demonstration projects, showcasing the actual effectiveness and potential of CCS technology to the public. This can include visiting CCS facilities, organizing open day events, and producing promotional materials and videos to showcase the application of technology. The government can encourage public participation in the discussion and decision-making process of CCS technology. Public hearings, symposiums, and workshops can be held to solicit public opinions and involve them in technology planning and decision-making, increasing public recognition. Strengthen communication and exchange with the public, and maintain transparency. Answer public questions and doubts, explain technical risks and measures, and timely update progress and achievements to establish public trust in CCS technology. Create easy to understand science popularization materials and information in education, and introduce CCS technology in a concise and concise manner. Explain the principles and processes of technology to the public through easily understandable charts, animations, and examples, helping them understand and accept relevant concepts. In today's internet age, partnerships with media, non-governmental organizations, and community organizations can be established. Collaborate with them to carry out promotional activities, hold lectures and seminars, and utilize their resources and networks to expand the dissemination of CCS technology. These measures require the joint efforts of the government, research institutions, enterprises, and non-governmental organizations to increase public awareness and understanding of CCS technology. Through extensive publicity, education, and participation, the public can better understand the potential of CCS technology.

With the increasing confidence in CCS policies in various countries around the world, more and more projects are entering different development stages. CCS has become an indispensable and important part of addressing climate change issues. Most importantly, CCS has been proven to be a safe and effective technology, the only one that can effectively reduce fossil fuel emissions, and also an important technology to solve emissions problems in the power industry. The cost of CCS will continue to decrease with the commercialization of more facilities. Against the backdrop of the rapid development of global new energy, CCS is a transit channel for realizing the new energy economy. Promising technologies such as CCS and hydrogen production, bioenergy and CCS technology, and direct air capture will further promote the commercialization and scale of new applications of CCS.

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