

Current status and development trend of carbon capture technology

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Abstract. In recent years, carbon dioxide capture (CCS) technology has garnered increasing attention as a crucial tool for addressing global climate change and air pollution. This paper delves into several carbon dioxide capture techniques, specifically pre-combustion capture, Oxy-fuel combustion capture, and post-combustion capture, and highlights the challenges encountered by each. Additionally, we have selected representative carbon dioxide capture projects from both domestic and international contexts for comprehensive analysis. Based on their specific circumstances, the anticipated future evolution of carbon dioxide capture technology is also envisioned.

Keywords: Carbon dioxide, CCS, policy, environment.

1. Introduction

With the escalating impact of human activities on the Earth's climate system, global warming has unequivocally emerged as an irrefutable reality. As widely acknowledged, excessive emissions of carbon dioxide constitute the primary driver behind the greenhouse effect [1]. Despite steady advancements in renewable energy development and utilization, fossil fuels continue to dominate the world's energy consumption structure in the short term, thereby impeding significant reductions in resulting carbon dioxide emissions. This poses a grave threat to global ecological equilibrium and sustainable development. Consequently, alongside long-term strategies aimed at curbing carbon emissions, there exists an urgent imperative to foster efficient technologies for capturing, utilizing, and storing carbon dioxide (CCUS) with a view to reduce the damage to the environment.

Presently, many developed countries consider CCUS (Carbon Capture Utilization Storage) technology as a pivotal means to address climate change concerns by encouraging enterprises to develop and implement this technology through legislative measures as well as financial support and tax incentives [2]. Developing countries are also actively following suit by formulating policies that promote the adoption of CCUS technology. For example, the Chinese government provides explicit support and guidance to CCUS technology development by incentivizing enterprise investment in research & development activities while fostering international cooperation within this domain. Since 2006, Chinese government has successively released more than 20 national policies related to CCUS, establishing its important position in addressing climate change and actively promoting the promotion of CCUS technology and the construction of demonstration projects [3]. These policies have greatly promoted the application of CCUS technology in China

Carbon dioxide capture technology represents a pivotal component within CCUS technologies. This paper mainly elucidates pertinent aspects pertaining to carbon dioxide capture technology. Over the past few decades, carbon dioxide capture technology has undergone a remarkable transition from laboratory research to commercial applications. Currently, According to the sequence of carbon capture and combustion processes, CCS technology is usually divided into three categories: pre combustion capture, during combustion capture (Oxy-fuel combustion technology) and post combustion capture [4]. These technologies have achieved varying degrees of effective separation and recovery of carbon dioxide; however, they also encounter challenges such as high energy consumption, elevated cost, and technological immaturity.



This paper aims to provide a comprehensive analysis of the present state of carbon dioxide capture technology, encompassing its technical principles, current applications, economic viability, and environmental consequences. Additionally, it will delve into potential future trends and challenges of this technology. The objective of this research is to offer a valuable reference for the enhanced development and implementation of carbon dioxide capture methods.

2. Carbon capture technology

Carbon capture technology, also known as Carbon Dioxide Capture and Storage (CCS), aims to isolate and concentrate carbon dioxide from the gases emitted during the combustion of fossil fuels, thereby mitigating the intensification of the greenhouse effect. Typically, CCS technology is categorized into three distinct types: pre-combustion capture, post-combustion capture, and oxyfuel combustion technology.

The schematic diagram of CCS is showed in Figure 1.

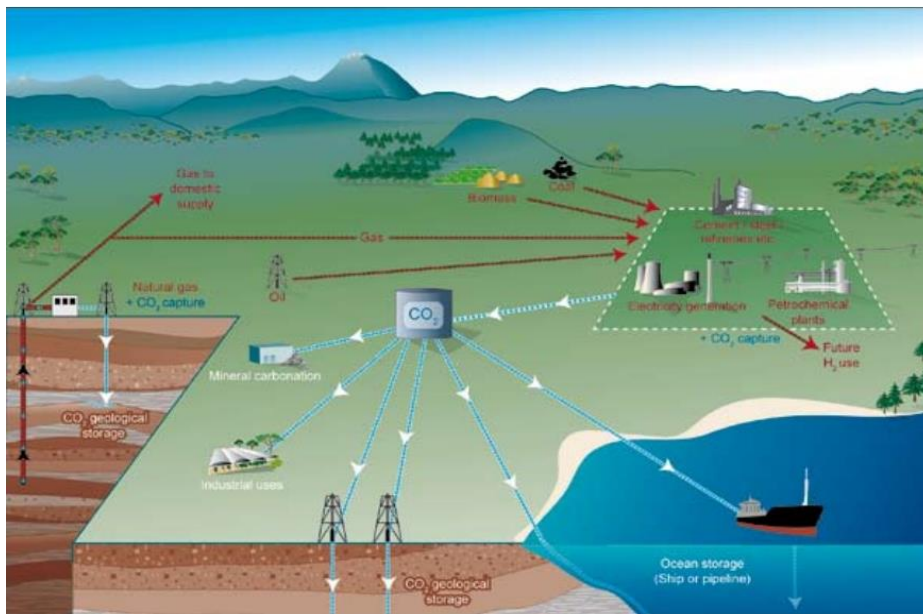


Figure 1. The schematic diagram of CCS [5].

2.1. Pre-combustion capture technology

Pre-combustion capture entails treating fuel prior to combustion to isolate and capture carbon dioxide. Generally, this technology is adopted in coal, biomass, and natural gas gasification processes to generate syngas [6]. This concentrated carbon dioxide capture process not only enhances efficiency but also significantly mitigates energy consumption and associated costs.

In industrial applications, pre-combustion capture technology often interfaces with advanced power generation systems, such as coal gasification or Integrated Gasification Combined Cycle (IGCC) [7]. These systems facilitate the efficient separation of carbon dioxide from fuel gases, contributing to greenhouse gas reduction efforts. The separated carbon dioxide can be processed through compression, liquefaction, and other methods for safe storage or other industrial purposes.

It's crucial to acknowledge that implementing pre-combustion capture technology poses challenges and relies on a comprehensive array of technical support and operational optimization. For instance, in the separation process, the appropriate absorbent or adsorbent must be selected to ensure the effective capture of carbon dioxide. Furthermore, strict treatment and storage of the captured carbon dioxide are imperative to prevent any leakage or environmental harm.

Simplified block diagram for IGCC with pre-combustion based CO2 capture technology is showed in Figure 2.

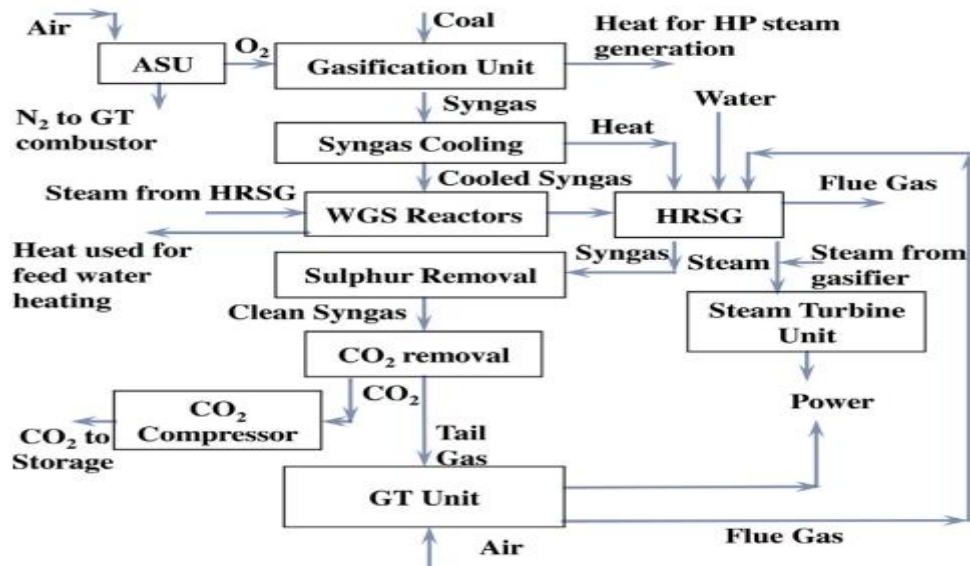


Figure 2. Simplified block diagram for IGCC with pre-combustion based CO₂ capture technology [8]

2.2. Post-combustion capture technology

Post combustion capture technology, a vital CCS method, effectively captures carbon dioxide from the generated flue gas after fuel combustion and energy release. At present, it has become one of the highly commercialized technologies, especially suitable for retrofitting existing power generation facilities, such as coal-fired power plants and natural gas power plants [9]. Due to the difficulty of achieving emission reduction through fuel replacement or pre-treatment technology in these facilities, post combustion capture technology has become a feasible option.

The essence of this technology resides in the effective separation of carbon dioxide from flue gas. Due to the low concentration of carbon dioxide generated during combustion (about 4 to 20 percent) and low pressure, advanced separation techniques are required. At present, chemical absorption and physical adsorption are the most commonly used methods.

2.2.1. Chemical absorption method

Chemical absorption is currently the most widely used method for post combustion capture technology [10]. Its basic principle is to use absorbent to react chemically with carbon dioxide in the flue gas, thereby separating it from the flue gas. The key is choosing suitable alkaline absorbents like ammonia solution, sodium carbonate solution, etc., with high CO₂ absorption capacity and selectivity.

In the chemical absorption method, the flue gas is first pretreated to remove impurities such as particles and acidic gases, and then enters the absorption tower. In the absorption tower, the flue gas comes into contact with the absorbent in reverse flow, and a chemical reaction occurs to generate compounds such as carbonates or bicarbonate, thereby achieving the capture of carbon dioxide[10]. Subsequently, the absorbent rich in carbon dioxide is sent to the regeneration tower, where the reaction is reversed by heating or reducing pressure, releasing pure carbon dioxide while achieving the regeneration and recycling of the absorbent. This method has high selectivity and efficiency, but it consumes a lot of energy, especially in the process of absorbent regeneration.

2.2.2. Physical adsorption method

Physical adsorption method uses the physical properties of the solid adsorbent surface to adsorb carbon dioxide in flue gas. It doesn't require chemical reactions, so the operating temperature is lower, making it suitable for treating low concentrations of carbon dioxide [11]. Commonly used adsorbents include activated carbon, zeolite molecular sieves, and the like, which have a large specific surface area and pore structure, and can provide abundant adsorption sites.

In the physical adsorption method, when the flue gas passes through the adsorption tower, carbon dioxide molecules are captured and fixed on the surface by adsorption sites on the adsorbent. As the adsorption process progresses, the adsorbent gradually saturates, and it is necessary to desorb the adsorbed carbon dioxide through methods such as heating, reducing pressure, or blowing to achieve the regeneration of the adsorbent.

2.2.3. Membrane separation method

The membrane separation method uses a specific material membrane to selectively penetrate gas molecules, thereby achieving the separation of carbon dioxide and other gases. This method has the advantages of low energy consumption, simple operation, and no secondary pollution. The selection of membrane materials is crucial, requiring high selectivity, high throughput, and good stability.

In membrane separation, when flue gas passes through membrane components, carbon dioxide is adsorbed or dissolved on one side of the membrane, and diffuses through the membrane layer to reach the other side. Due to the varying solubility and diffusion rates of different gas molecules in the membrane, effective separation of carbon dioxide from other gases can be achieved.

2.3. Oxy-fuel combustion technology

Oxy-fuel combustion, another application of CCS technology, involves augmenting the carbon dioxide concentration in exhaust gas via combusting fuel within an oxygen-enriched atmosphere, thus facilitating its capture and storage. This technology is considered as a highly efficient carbon capture pathway due to its potential to substantially diminish exhaust gas volume and yield a high-purity carbon dioxide stream, thereby reducing the expense and energy consumption associated with subsequent capture and separation.

In Oxy-fuel combustion technology, the fuel (usually coal or natural gas) is burned in a gas mixture containing a high concentration of oxygen, instead of the traditional air. Given that approximately 78% of the air is nitrogen, which does not participate in the combustion reaction, its presence dilutes the concentration of carbon dioxide in the flue gas, making subsequent capture difficult and costly.[12] By using pure oxygen or an oxygen-rich mixture as an oxidizer, the nitrogen content in the flue gas can be significantly reduced, thereby increasing the concentration of carbon dioxide, frequently surpassing 90%.

The oxygen supply is crucial to the success of Oxy-fuel combustion technology. In practical applications, this is usually achieved through an Air Separation Unit (ASU), which produces oxygen-rich gases by compressing air and utilizing distillation or membrane separation techniques. This oxygen-rich gas is then fed into the combustion chamber, where it burns with the fuel. Since there is no nitrogen involved in the combustion process, the resulting flue gas is mainly composed of water vapor, carbon dioxide, and small amounts of other gases [13].

The process of capturing carbon dioxide is relatively simple. Because the concentration of carbon dioxide in the flue gas is very high, the flue gas can be cooled to condense water vapor and further concentrate the carbon dioxide. The CO₂ can then be prepared for transport or stored underground through a compression and purification process.

Although Oxy-fuel combustion technology has many advantages, it also faces some challenges. The first is the higher energy cost of oxygen production, because the air separation unit consumes more energy. In addition, since combustion in an oxygen-rich environment may produce higher flame temperatures, this can lead to increased thermal stress on equipment materials, which puts higher demands on the design and materials of combustion chambers and other related equipment [4]. At the same time, in order to maintain the appropriate combustion temperature, it may be necessary to recycle a portion of the combustion product gas or add other types of diluents.

Block diagram of oxyfuel combustion capture system is showed in Figure 3.

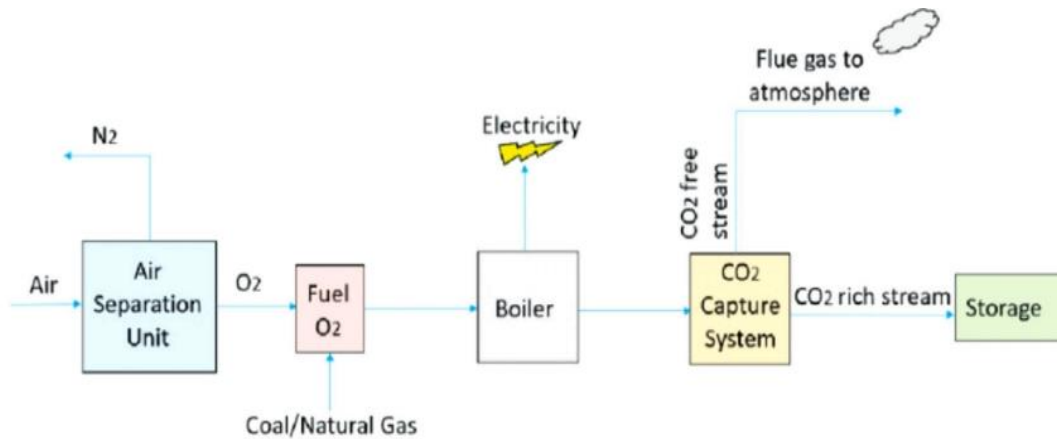


Figure 3. Block diagram of oxyfuel combustion capture system [14].

3. The challenges of current CCS technologies

At present, CCS technology, as one of the important means to reduce carbon dioxide emissions, has attracted wide attention in recent years. However, despite its promising prospects, CCS technology still faces many challenges and problems in its practical application.

3.1. Insufficient technical maturity

Although CCS technology has made some progress, there are still some technical problems and risks in practical applications. At present, the main CCS technologies include chemical absorption method, physical adsorption method, membrane separation method, etc. Although the chemical absorption method has high capture efficiency, it has some problems such as high energy consumption, absorbent loss and equipment corrosion. Physical adsorption and membrane separation methods Due to the selectivity and capacity of the adsorbent or membrane material, the capture efficiency is usually low and insufficient to handle large-scale emissions. The energy used in CCS technology is large, often from fossil fuels, which themselves produce carbon dioxide emissions [15]. In addition, CCS technology often requires specialized equipment and facility support, including efficient absorbers, sophisticated separation units, and reliable storage and transportation systems. These devices are not only expensive, but also very demanding for operation and maintenance.

Due to the lack of technology maturity, the current equipment investment and operating costs of CCS technology are high, and the economy is poor. The high cost of rolling out CCS technology is difficult for many companies and even industries to accept. This is not only a pressure on businesses, but also an issue for governments to consider [16]. Without government subsidies and related policies, CCS technology can hardly compete with other technologies. Therefore, it is urgent to improve the maturity and reliability of CCS technology, reduce the cost of technology, and improve the economic benefits of CCS technology.

3.2. Environmental impact and public acceptance

Although CCS technology is designed to reduce the concentration of carbon dioxide in the atmosphere and reduce the greenhouse effect, it can also have certain environmental impacts. A lot of energy is required during the carbon dioxide capture process, especially during the carbon dioxide capture and compression phase. This can lead to indirect greenhouse gas emissions that partially offset the reduction. The process of sequestering carbon dioxide can also pose geological and ecological risks, such as groundwater contamination or surface subsidence, and there is a potential risk of leakage [13]. Therefore, before promoting CCS technologies, adequate environmental impact assessments need to be carried out to ensure that their impact on the environment is manageable.

In addition, public acceptance of CCS technology is also an important factor affecting its promotion. At present, because CCS technology is relatively professional, and the public has little exposure to relevant information in their daily lives, they do not have a deep understanding of it. This results in a lack of information for the public to assess the value and impact of CCS technology. And there are public concerns about the safety and long-term impact of CCS technology. Since CCS technology involves storing carbon dioxide underground for long periods of time, the public may be concerned about possible leaks during storage and possible negative impacts on the environment and society after a leak [16]. Such concerns have limited public acceptance of CCS technology to some extent. Therefore, to strengthen the publicity and education of CCS technology in the face of the public is an important prerequisite for promoting this technology.

3.3. Policy support and supervision

The development of CCS technology needs the support of governments and relevant departments. However, there is a global lack of a coherent policy framework for carbon capture. Different countries and regions have different levels of support and regulations for CCS technologies, which can make cross-border cooperation and project implementation difficult. And many countries have yet to establish clear laws and regulations to guide the implementation of carbon capture projects. This includes aspects such as long-term liability for CO₂ sequestration, requirements for environmental impact assessments and the definition of liability for spills. Policy instability or changes may also affect the economic viability of carbon dioxide capture projects [10]. For example, the reduction or elimination of government subsidies, changes to the carbon pricing mechanism, etc., may have an impact on the investment decision of the project.

In the field of regulation, CCS technology involves the regulation of many fields, including energy, environmental protection, mining and geological exploration. Regulatory systems in these areas may overlap or be inconsistent with each other, adding complexity and cost to the project. Addressing these issues will require national and international efforts to develop clear policies and regulations to facilitate the development of CCS technologies.

4. The introduction CCS technology project

From a global perspective, countries such as the United States, the United Kingdom, Australia, Canada, and China are vigorously developing CCUS testing, demonstration, and industrial scale projects, with a good development momentum. The development characteristics of CCS industrial demonstration projects are gradually increasing in number and scale.

4.1. CIUDEN CCS project

One of the current initiatives in CCS research and development in Europe is the El Bierzo Technology Development Plant (TDP), which is supported by the Spanish government through the Energy Foundation (CIUDEN) [17]. CIUDEN is a research and development institution established by the Spanish government in 2006, fully committed to collaborative research between CCS and CCT, thereby contributing to strengthening the industrial and technological foundation of Spain and even Europe [15]. The main goal of CIUDEN in the carbon dioxide capture program is to research, develop, and demonstrate efficient, economical, and reliable CCS technology as well as third-generation flue gas purification technology, through the design and operation of large-scale comprehensive testing facilities for carbon dioxide capture in power generation. The CCS device of the factory includes a 20 MW capacity PC boiler, a 30 MW capacity CFB boiler, a fuel preparation device, a biomass gasification device, a flue gas purification device, and a carbon monoxide treatment device. In addition, the project also supports the OXYCFB300 Compostilla project, which is a demonstration project based on circulating fluidized bed (CFB) supercritical oxygen combustion technology, with the goal of achieving carbon dioxide storage in salt water layers [18].

Schematic diagram of the CIUDEN's Capture TDP is shown in Figure 4.

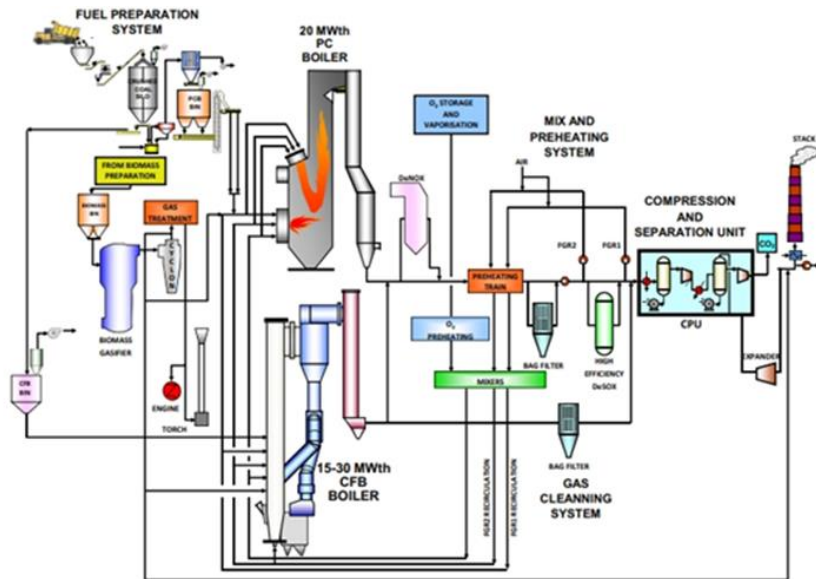


Figure 4. Schematic diagram of the CIUDEN's Capture TDP [17].

By establishing official websites, social media accounts, and other online platforms, CIUDEN provides the public with access to project information, and regularly holds public education activities such as lectures and seminars to popularize the knowledge, significance, and potential impact of CCS technology to the public [19]. Meanwhile, CIUDEN focuses on building trust with the public, eliminating misunderstandings and doubts by promptly responding to their concerns and doubts. The project team will actively communicate with the public, explain the significance and value of the project, as well as the potential environmental and social impacts it may bring. These measures have increased public awareness and understanding of CCS projects, greatly reduced public resistance to CCS, and promoted the development of CCS technology in Europe

4.2. CCUS project of China National Energy Group Taizhou Power Plant

The CCUS project of China National Energy Group Taizhou Power Plant is a typical representative of the application of CCS technology in China. Through this project, not only can carbon dioxide emissions from thermal power plants be significantly reduced, but the captured carbon dioxide can also be widely applied in industries such as industry and food, achieving resource reuse.

The National Energy Group Taizhou Power Plant CCUS project is located in Taizhou City, Jiangsu Province, and is the largest thermal power carbon capture, utilization, and storage project in Asia. This project can capture 500000 tons of carbon dioxide annually, with a capture rate of over 90%, and the purity of dry carbon dioxide produced exceeds 99% [14]. The technical process adopted in the project includes three main parts: water washing tower, absorption tower, and regeneration tower. The flue gas first goes through a water washing tower to cool down and remove impurities, and then reacts with an amine solution in the absorption tower to capture over 90% of carbon dioxide. Finally, high-purity carbon dioxide and lean amine solution are separated in the regeneration tower. The former is transported to the storage tank, while the latter is returned to the absorption tower for recycling.

The Taizhou Power Plant CCUS project is not only technologically advanced, but also economically stable and profitable. The project team successfully identified users in fields such as oilfield oil displacement, welding manufacturing, and food grade dry ice through market research, ensuring that the captured carbon dioxide can be effectively utilized and achieving a 100% absorption rate. This not only provides guarantees for the sustainable operation of the project, but also explores new avenues for the commercial application of CCUS technology.

5. Conclusion

This article summarizes the various stages of CCS technology and some engineering demonstration projects at home and abroad, analyzes the challenges faced by the current application of CCS technology, and based on the above research results, makes the following prospects for CCS technology:

5.1. In terms of technological development and economic benefits

CCS technology mainly includes three stages: capture, transportation, and storage. In the capture process, future development will focus on improving capture efficiency and reducing energy consumption. In the transportation sector, future research will focus on improving transportation efficiency and safety. The technological innovation in the storage process will focus on improving storage capacity and long-term security.

At present, the cost of CCS technology is relatively high, which is one of the main factors limiting its large-scale application. Therefore, the future development trend will focus on reducing costs and improving economic feasibility. With the continuous progress and large-scale application of technology, the cost of CCS technology will gradually decrease.

5.2. In terms of policy support and international cooperation

Government policy support is crucial for the development of CCS technology. In the future, governments around the world may introduce more policies to encourage the research and application of carbon capture technologies, such as tax incentives, financial support, and regulatory development. The research and application of CCS technology require cross-border cooperation. In the future, international organizations and governments may strengthen cooperation in this field, jointly promoting the formulation of technical standards, exchange of experiences, and promotion of best practices.

5.3. In terms of environmental protection and public recognition

By capturing and sequestering carbon dioxide, greenhouse gas emissions can be reduced and the impact of global climate change can be mitigated. At the same time, CCS technology can also promote the optimization and transformation of energy structure, and promote the development of green and low-carbon economy.

In summary, the development of CCS technology will be multifaceted. With the continuous progress in these fields, CCS technology is expected to become one of the key tools for mitigating climate change and achieving sustainable development in the future.

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