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The Role, Challenges, and Future Prospects of CCS in Global Climate Governance

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Abstract. Carbon Capture and Storage (CCS) is an important technology for reducing carbon emissions and achieving global carbon neutrality goals. This paper reviews the development status, main applications, challenges, and future prospects of CCS in global climate governance. The study introduces the basic principles of CCS and discusses its applications in hard-to-abate industries, such as steel, cement, and chemical production. These industries produce large amounts of carbon dioxide emissions, which are difficult to reduce only through renewable energy and energy efficiency improvements. This paper also discusses the role of negative emission technologies, including Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon with Capture and Storage (DACCS). The results show that CCS has great potential to support industrial emission reduction and global climate goals. However, its large-scale development still faces challenges, including high costs, limited infrastructure, technical difficulties, and concerns about storage safety. In the future, CCS development will require technological improvement, policy support, and international cooperation. CCS should work together with renewable energy and other low-carbon technologies to help achieve long-term climate goals.

Keywords: Carbon Capture and Storage, Climate Governance, Carbon Neutrality, Deep Decarbonization, Negative Emission Technologies

1. Introduction

1.1. Background and context

Global climate change has become an important environmental issue affecting sustainable economic and social development. With the implementation of the Paris Agreement and the increasing number of countries proposing carbon peaking and carbon neutrality goals, reducing carbon dioxide emissions effectively has become a key issue in global climate governance [1-3]. At present, greenhouse gas reduction mainly depends on several approaches, including energy transition, improving energy efficiency, Carbon Dioxide Removal (CDR), and Carbon Capture and Storage (CCS) [1, 2, 4]. Among these approaches, renewable energy sources such as wind and solar power can reduce the use of fossil fuels, while improving energy efficiency can reduce carbon emissions per unit of production. In addition, afforestation and negative emission technologies can increase the removal of carbon dioxide from the atmosphere [4, 5].

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1.2. Research gap

In recent years, research on CCS has increased rapidly. Existing studies mainly focus on carbon capture technologies, CO_2 transportation and storage, safety monitoring, economic evaluation, and commercial applications, providing an important theoretical foundation for CCS development [6-9]. However, some issues still require further discussion.

Comprehensive comparisons among different CCS pathways are still limited. Current studies on industrial CCS, BECCS, and DACCS mainly analyze each technology separately, while comparisons of their application scenarios, emission reduction targets, and development characteristics are relatively insufficient [4, 10, 11].

1.3. Objectives of the study

(1) To identify the major challenges faced by CCS commercialization, including technical, economic, policy, and environmental issues [12-16].

(2) To analyze future development trends of CCS and its role in achieving deep decarbonization under the background of global climate governance [1-3, 17].

1.4. Significance of the study

By reviewing recent studies on CCS development, this paper systematically summarizes its technological progress, major application areas, current challenges, and future development trends. This helps to better understand the role and development characteristics of CCS in global climate governance [4-7, 18].

2. Literature review

2.1. Overview of existing research

With the continuous development of global climate governance, CCS has become an important research topic in the fields of energy, environment, and climate change [1, 6, 7]. Existing studies focus not only on the development of key CCS technologies but also on industrial applications, economic feasibility, and its role in global climate governance. Based on previous studies, three main viewpoints have been developed [8, 9, 12].

The forst viewpoint focuses on the development of CCS technologies and engineering applications. Many studies have been carried out on carbon capture efficiency, CO_2 transportation systems, geological storage safety, and cost reduction [6, 19-21]. These studies generally believe that the maturity of CCS technology has improved in recent years and its commercial application prospects have become better [6, 16, 18]. However, they also point out that high capture costs, energy consumption increases, and insufficient infrastructure remain major barriers to large-scale CCS development [12-14]. Therefore, continuous technological innovation and policy support are needed in the future [15, 16].

The second viewpoint takes a more cautious attitude toward large-scale CCS deployment. Some researchers argue that excessive dependence on CCS may slow down energy system transformation and create a "carbon lock-in" effect, which may reduce the development of renewable energy [5, 22, 23]. At the same time, some studies suggest that many climate scenarios predicting future CCS deployment are based on relatively ideal assumptions. Uncertainties still exist in economic feasibility, public acceptance, and long-term storage safety [5, 14, 16]. Therefore, these studies

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suggest that CCS should be considered as an important supplementary technology rather than the only solution. It should develop together with renewable energy, energy efficiency improvement, and other negative emission technologies [2, 4].

Although existing studies have generally reached an agreement on the important role of CCS in global climate governance, disagreements still exist regarding its economic feasibility, deployment scale, and future strategic position [12, 14, 17]. Different research perspectives complement each other and show that CCS research has gradually shifted from focusing only on technology itself to a broader perspective of climate governance. These studies provide an important theoretical foundation for future research.

2.2. Research limitations of existing literature

Although CCS-related research has achieved many results in recent years, some limitations still exist.

Most studies mainly focus on CCS technological innovation, economic evaluation, or specific industrial applications, while fewer studies analyze the role of CCS from the perspective of global climate governance [7, 8, 11]. With the continuous development of global carbon neutrality goals, CCS is not only an engineering technology but also closely related to international climate policies, global emission reduction cooperation, and climate governance systems. Therefore, a broader analysis is needed [1-3].

Comprehensive comparisons among different CCS pathways are still limited. Technologies such as industrial CCS, BECCS, and DACCS are usually studied separately, while comparisons of their emission reduction targets, application scenarios, governance functions, and strategic values are insufficient [4, 10, 11]. In fact, these technologies have different roles in achieving global net-zero emissions, and their advantages and suitable conditions need further discussion [4, 5].

In addition, existing studies often analyze CCS development from a single perspective, such as technology, economy, or environment. However, the interactions among technological development, policy support, market mechanisms, public acceptance, and international cooperation have received relatively limited attention [13-15]. Future studies should focus more on comprehensive analysis to better identify the key factors affecting large-scale CCS deployment [24, 17].

Therefore, it is necessary to systematically organize and compare existing studies, summarize different viewpoints from the perspective of global climate governance, and identify future development trends of CCS. This can provide a more comprehensive reference for future research.

2.3. Relationship with this study

This paper mainly compares different CCS pathways, including industrial CCS, BECCS, and DACCS, in terms of emission reduction targets, application scenarios, and their roles in global climate governance. It also summarizes the agreements and differences among different studies [4, 10, 11]. Meanwhile, based on reports from international organizations and important recent studies, this paper analyzes the future development trends of CCS under the background of global carbon neutrality [1, 3, 18].

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3. Research methods

3.1. Research design

As a review study, this paper does not include field surveys, experiments, or model construction. Instead, it uses published academic papers and reports from international organizations as the main research materials. By comparing different studies, this paper summarizes the development process, research focuses, and major debates of CCS, providing a theoretical basis for further analysis [1-3].

3.2. Data sources

The research materials mainly come from reports published by international organizations and academic studies from both China and other countries. The international reports mainly include assessment reports from the Intergovernmental Panel on Climate Change (IPCC), reports from the International Energy Agency (IEA), and annual reports from the Global CCS Institute. These reports provide important information for analyzing the current development status, policy background, and future trends of global CCS development [1-3, 18].

During the literature selection process, studies closely related to CCS technology development, global climate governance, and carbon neutrality strategies were selected. The representativeness, reliability, and timeliness of the literature were also considered [7, 8, 11].

3.3. Data collection methods

The literature collection process followed three principles: relevance, reliability, and timeliness. First, research keywords were determined based on the research topic. Relevant studies were searched through databases such as Web of Science and Google Scholar. In addition, reports from international organizations, including IPCC, IEA, and Global CCS Institute, were also collected [1, 3, 18].

The initial search identified more than 100 related studies. Then, the literature was screened based on titles, abstracts, and full texts. Duplicate studies and studies with low relevance to the research topic were removed. At the same time, representative classical studies and important recent research were retained. Finally, about 30 representative academic papers and international reports were selected as the main sources for this study, providing a foundation for further analysis.

3.4. Data analysis methods

This paper mainly uses inductive analysis and comparative analysis to organize and analyze existing literature.

The inductive analysis method is used to summarize the current development status, major application areas, existing challenges, and future development trends of CCS [6, 7, 12]. The comparative analysis method is used to compare different CCS pathways, including industrial CCS, BECCS, and DACCS, focusing on their emission reduction targets, application scenarios, and roles in global climate governance. It also analyzes the similarities and differences among different studies [4, 10, 11].

Based on these analyses, this paper systematically summarizes existing research results, identifies the main characteristics and future trends of CCS development, and provides a basis for further discussion and analysis.

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4. Results

4.1. Current status of CCS deployment

Driven by global carbon neutrality goals and national policy support, the CCS industry has entered a period of rapid development. The number of CCS projects has continued to increase, and application areas have gradually expanded. CCS is gradually moving from early demonstration projects toward commercial-scale deployment [3, 18].

From a regional perspective, current CCS projects are mainly concentrated in North America, Europe, and the Asia-Pacific region, but development patterns vary among different regions [18]. The United States and Canada have developed relatively complete CCS industrial chains based on their mature oil and gas industries, existing CO_2 transportation networks, and tax incentive policies. Europe mainly promotes CCS development through the European Union Emissions Trading System (EU ETS) and international cooperation mechanisms, with a focus on cross-border CO_2 transportation and offshore storage projects in the North Sea. In recent years, China has actively promoted CCUS demonstration projects and carried out pilot applications in industries such as coal power, coal chemical production, cement, and steel. The number of projects has increased rapidly [15, 18]. These regional differences are closely related to energy structures, industrial foundations, policy support, and geological storage conditions in different countries [12, 14].

From the perspective of industrial applications, CCS is currently mainly used in high-emission industries, including natural gas processing, chemical production, power generation, cement, steel, and oil refining. Among these sectors, industrial applications have become one of the fastest-growing areas of CCS development. This indicates that the focus of CCS is gradually shifting from traditional energy industries to hard-to-abate industries such as steel, cement, and chemical production [24-26]. This trend further shows that CCS will play an increasingly important role in future industrial decarbonization [2, 24].

4.2. Role of CCS in climate mitigation

Existing studies generally agree that CCS is an important pathway for achieving global deep decarbonization. However, the demand for CCS varies among different industries. Its emission reduction role is mainly reflected in the following aspects [1, 2, 24].

For hard-to-abate industries such as steel, cement, and chemical production, a large amount of CO_2 emissions comes from industrial processes. Therefore, emissions cannot be completely eliminated only through renewable energy replacement or energy efficiency improvement. CCS can directly capture CO_2 generated during industrial production and is considered an important technology for industrial low-carbon transformation. It is also one of the most promising emission reduction solutions currently available [24-26].

Therefore, future CCS development is expected to gradually shift from traditional coal-fired power plants toward industrial sectors [24, 26].

CCS is also an important foundation for negative emission technologies [4, 10]. BECCS combines biomass energy use with carbon storage to achieve net negative emissions, while DACCS directly captures CO_2 from the atmosphere. These technologies can help offset unavoidable emissions from sectors such as aviation and agriculture [4, 5, 27]. Therefore, negative emission technologies are expected to play an increasingly important role in achieving global net-zero emission goals [1, 2].

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CCS is not a competitor to renewable energy but a complementary technology. Future global emission reduction requires the combined development of energy transition, energy efficiency improvement, CCS, and other technologies to support the achievement of global carbon neutrality goals [1-3].

4.3. Major challenges

Although CCS has significant emission reduction potential, its large-scale deployment still faces many challenges, including economic, technological, infrastructure, and social issues. These challenges influence and restrict each other [12-15].

High construction and operation costs remain the biggest barriers to CCS commercialization. The carbon capture process usually accounts for a large proportion of the total CCS cost, making many projects difficult to achieve economic feasibility [6, 11, 12]. At present, many CCS projects still require financial subsidies, tax incentives, or carbon market support to maintain operation. Therefore, high costs increase the dependence of CCS on policy support [13, 15].

Overall, high costs make CCS more dependent on policy support, while policies and infrastructure directly influence commercialization. Public acceptance and regulatory systems also affect long-term operation. Therefore, large-scale CCS deployment in the future requires cooperation among technological innovation, policy support, market mechanisms, and social participation [14, 15, 17].

4.4. International differences

Due to differences in resource conditions, industrial structures, and policy environments, CCS development models vary significantly among different countries and regions [14, 18]. Table 1 presents the main drivers as well as the key strengths and weaknesses of CCS technologies in different countries.

Table 1. Comparison between different countries and regions

Region	Main Drivers	Main Advantages	Main Challenges
United States	45Q tax credits, Inflation Reduction Act, and other financial incentives	High commercialization level, mature oil and gas industry, developed CO_2 transportation networks	High project costs and dependence on policy support
Europe	EU ETS, European Green Deal, and international cooperation	Strong regulatory systems, experience in cross-border transport and offshore storage	High construction costs and complex international coordination
China	Carbon neutrality goals and industrial emission reduction needs	Rapid growth of demonstration projects and large industrial application potential	Infrastructure and commercialization systems need further improvement

The United States has mature oil and gas industries and well-developed CO_2 transportation networks. Supported by policies such as the 45Q tax credit and the Inflation Reduction Act, it has established a relatively complete financial incentive system, promoting the development of many commercial CCS projects [15, 18].

Europe places greater emphasis on regulatory systems and international cooperation. Through the EU Emissions Trading System (EU ETS) and the European Green Deal, Europe promotes CCS development while actively building cross-border CO_2 transportation networks and North Sea

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offshore storage projects. Environmental safety and long-term regulation are important priorities [14, 18].

China started CCS development relatively later, but progress has been rapid in recent years. With the introduction of the carbon neutrality goals, China has continued to promote CCUS demonstration projects and pilot applications in industries such as coal power, coal chemical production, cement, and steel [18, 28]. In the future, China's CCS development will focus more on deep emission reduction in industrial sectors and promote cooperation between CCUS, renewable energy, and hydrogen industries [26, 28].

Though the United States, Europe, and China have different development pathways, their experiences all show that policy support, industrial demand, infrastructure development, and technological innovation are key factors driving large-scale CCS deployment [14, 15, 17]. In the future, countries need to develop CCS strategies based on their own resources and industrial conditions, strengthen international cooperation, and jointly promote the application of CCS in global climate governance [1, 3].

5. Discussion

5.1. Comparison with existing studies

The results of this study are generally consistent with previous research. International organizations such as the IPCC and the International Energy Agency (IEA) have pointed out that CCS will play an important role in hard-to-abate industries and negative emission technologies in most scenarios for achieving global net-zero emissions. This is consistent with the analysis of CCS's role in industrial decarbonization and climate governance in this study.

Previous studies generally agree that CCS has significant emission reduction potential, but its development is still affected by economic costs, technological maturity, and social acceptance. For example, some studies emphasize that technological progress can improve capture efficiency and reduce costs. However, other studies focus more on the potential carbon lock-in risk caused by CCS and its possible impact on the speed of energy transition.

Based on existing research, CCS is important but cannot solve climate change problems independently. Future CCS development needs to be combined with energy transition, renewable energy development, and other low-carbon technologies. Meanwhile, differences among studies indicate that the future scale and development pathway of CCS will continue to be influenced by technology costs, policy environments, and social factors.

5.2. Policy and practical implications

According to the analysis of this study, large-scale CCS deployment requires the combined support of technological development, market mechanisms, and government policies.

First, carbon pricing systems and economic incentive policies should be further improved. Since CCS projects currently have high construction and operation costs, reasonable carbon pricing mechanisms, tax incentives, and financial support can reduce investment risks and improve the commercial feasibility of CCS projects.

Second, CO_2 transportation and storage infrastructure should be strengthened. CCS involves multiple stages, including capture, transportation, and long-term storage. A complete CCS industrial chain is difficult to build by individual companies alone. Therefore, regional CO_2 transportation

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networks and shared storage facilities should be developed to improve the overall efficiency of CCS systems.

Third, long-term storage management systems should be improved. Since geological storage involves long-term environmental safety issues, effective monitoring, reporting, and verification (MRV) systems are needed. Risk assessment and environmental regulation should also be strengthened to improve public acceptance of CCS technology.

Finally, CCS policy support should not only focus on project construction but also cover the entire process, including technology research, infrastructure development, market mechanisms, and long-term regulation. This will help promote the transition of CCS from demonstration projects to large-scale commercial applications.

5.3. Future research directions

Future CCS research should focus on the following aspects.

Carbon capture costs should be further reduced and the economic performance of CCS should be improved. Currently, the capture process remains one of the most expensive parts of CCS. Therefore, developing more efficient and low-energy capture materials and technologies is an important direction for promoting CCS commercialization.

The overall efficiency of CCS systems should be improved. This includes optimizing CO_2 transportation networks, improving storage resource utilization, and strengthening cooperation among capture, transportation, and storage processes.

Research on long-term CO_2 storage safety monitoring should be strengthened. Stable and safe geological storage is an important foundation for public acceptance of CCS. Therefore, more accurate monitoring technologies and risk assessment systems should be developed.

Policy mechanisms supporting CCS development should be improved. These include carbon pricing systems, market incentives, and long-term regulatory frameworks. These measures can promote the transition of CCS from demonstration projects to large-scale commercial applications.

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