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Review

Advancing “Carbon Peak” and “Carbon Neutrality” in China: A Comprehensive Review of Current Global Research on Carbon Capture, Utilization, and Storage Technology and Its Implications

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Cite This: *ACS Omega* 2023, 8, 42086−42101

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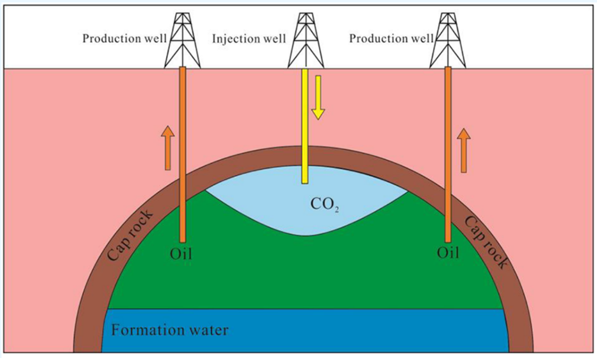

ABSTRACT: Carbon capture, utilization, and storage (CCUS) technology plays a pivotal role in China’s “Carbon Peak” and “Carbon Neutrality” goals. This approach offers low-carbon, zero-carbon, and even negative-carbon solutions. This paper employs bibliometric analysis using the Web of Science to comprehensively review global CCUS progress and discuss future development prospects in China. The findings underscore it as a prominent research focus, attracting scholars from both domestic and international arenas. China notably leads the global landscape in terms of research paper output, with the Chinese Academy of Sciences holding a prominent position in total published papers. The research predominantly centers on refining geological storage techniques and optimizing oil and gas recovery rates. Among the CCUS pathways, enhanced oil recovery technology stands out due to its relative maturity and commercial applicability, particularly within the conventional oil and gas reservoirs. The application potential of enhanced gas recovery technology, especially in the Sichuan and Ordos Basins in China, necessitates robust research and demonstration efforts. Within China’s current energy landscape, “Blue Hydrogen” emerges as the primary solution for hydrogen production in conjunction with CCUS technology. The underground coal gasification approach holds significant promise as a hydrogen production avenue, albeit with inherent ecological and environmental challenges tied to geological storage that require meticulous consideration. The establishment of effective risk identification and evaluation methodologies for geological storage is imperative. The trajectory ahead involves a strategic convergence of policy, technology, and market dynamics to enhance China’s CCUS policy framework, legislative framework, standardization initiatives, and pioneering technological advancements. These collective efforts converge to outline an exclusive development pathway in China. This study assumes a pivotal role in accelerating CCUS technology research and deployment, enhancing oil and gas recovery efficiency, and ultimately realizing the overarching goals of a “Dual Carbon” future.

0. INTRODUCTION

The global warming caused by greenhouse gas emissions has become a significant ecological and environmental issue on a global scale.[1−3] Climate anomalies, droughts, glacial melting, and rising sea levels have threatened human, animal, and plant production and livelihoods. Energy conservation and emission reduction have become the keys to addressing this problem.[4−7] The progression of industrialization has ushered in a consequential surge in atmospheric CO_2 concentrations, potentially soaring to 570 ppm by 2100. This impending surge stands poised to trigger a cascading effect, propelling global temperatures to ascend by 1.9 °C, while simultaneously instigating a substantial sea-level surge, reaching a towering elevation of 3.8 m.[8,9] Compounding the severity of this predicament, the World Health Organization (WHO) has underscored air pollution and climate change as the preeminent perils to public well-being.[10−12] Forecasts forewarn that the time frame spanning 2030−2050 could bear witness to an alarming escalation in mortality rates, attributed to the amplified prevalence of sweltering temperatures, exacerbating malnutrition and precipitating a distressing upswing in premature fatalities stemming from afflictions such as stroke, cancer, pulmonary disorders, and cardiovascular malaise.[13−15]

China and the United States collectively account for approximately one-third of global CO_2 emissions. The most substantial release of CO_2 is pinpointed in chemical plants and thermal power facilities. CO_2 dominates the landscape of

Received: August 30, 2023
Revised: October 16, 2023
Accepted: October 20, 2023
Published: November 2, 2023

https://doi.org/10.1021/acsomega.3c06422

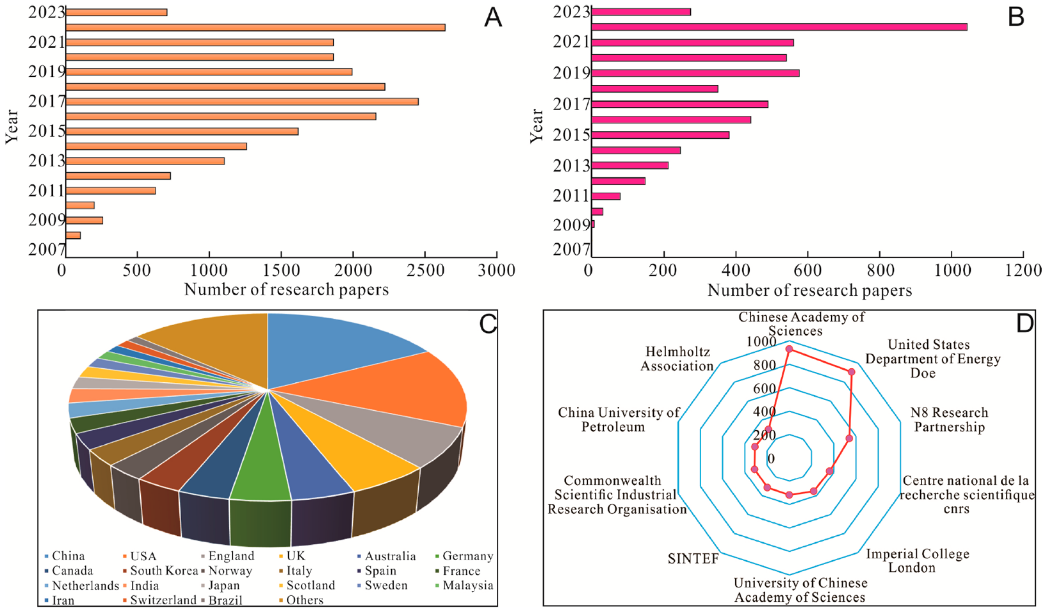

Figure 1. Global research survey in the CCUS (data as of July 13, 2023). (A) Total number of global research papers; (B) number of SCI papers published by Chinese scholars; (C) major source regions of global papers; (D) top 10 global institutions by publication volume.

greenhouse gas emissions, comprising a substantial 85%, with fossil fuel consumption singularly responsible for nearly 58.8%. The confluence of an expanding global populace and the currents of globalization have precipitated a noteworthy surge in the utilization of fossil fuels across many nations.[16−18] In response to the formidable challenge posed by uncontrollable emissions, the proposition of carbon neutrality has emerged as a strategic approach. Carbon neutrality constitutes attaining a net zero CO_2 emission state, meticulously achieved by maintaining a harmonious equilibrium between carbon emissions and carbon absorption. In earnest pursuit of this aspiration, members of the European Union have set their sights on a substantial 40% reduction in greenhouse gas emissions by the year 2030, thereby setting the trajectory toward the overarching objective of realizing carbon neutrality by 2050.

Carbon capture, utilization, and storage (CCUS) technology has been internationally recognized as one of the most effective and promising methods to reduce greenhouse gas emissions.[19,20] In this context, China has set forth its “Dual Carbon” goals for the first time, which include achieving the “Carbon Peak” and “Carbon Neutrality” targets. “Carbon Peak” refers to reaching a point in time when CO_2 emissions reach their peak and gradually decline thereafter. “Carbon Neutrality” refers to balancing the total amount of direct and indirect CO_2 or greenhouse gas emissions produced by a country, company, product, activity, or individual within a certain period.[21−23] This balance is achieved through measures such as afforestation, energy conservation, and emission reduction, offsetting the CO_2 or greenhouse gas emissions generated by oneself, and reaching a state of stable greenhouse gas emissions or relative “zero emissions”.[24−27]

In recent years, international organizations such as the Society of Petroleum Engineers (SPE) and the Oil and Gas Climate Initiative (OGCI) have formed dedicated CCUS technology guidance committees and initiatives.[28,29] China’s Industry Technology Innovation Strategic Alliance has also been established, resulting in significant technological progress. Conducting global research on CCUS technology progress and implementing pioneering engineering practices domestically are of vital significance in achieving the “Dual Carbon” goals.[30]

In the past decade, there have been many review papers on the progress of CCUS technology. These papers primarily focus on carbon capture and storage (CCS), enhanced oil recovery (EOR), and environmental benefits. This paper employs a bibliometric methodology, utilizing the Web of Science (WOS) database, to provide a comprehensive review of the global progress in CCUS technology. Additionally, it outlines the potential trajectories and prospects for advancing CCUS technology development in China. The findings underscore CCUS as a prominent research focus, attracting scholars from both domestic and international arenas.

In contrast, this paper not only encompasses these methods but also introduces additional technologies like hydrogen production technology coupled with CCUS and enhanced gas recovery (EGR). Moreover, it systematically presents a framework for CCUS in achieving the “Dual Carbon” goals in China, which have been proposed as part of a conceptual framework to address carbon emissions and achieve carbon neutrality. In conjunction with this critical analysis, a strategic array of recommendations is elucidated, intended to serve as a guiding compass for the trajectory of future enhancements and advancements in this pivotal domain.

1. A BIBLIOMETRIC REVIEW OF GLOBAL PROGRESS IN CCUS TECHNOLOGY RESEARCH

1.1. Literature Analysis. Using the WOS platform for literature retrieval and bibliometrics is a crucial approach to understanding technology’s global status and progress.[31,32] In this paper, we employed bibliometric methods to analyze relevant literature from the Science Citation Index Expanded (SCI-E) database on the WOS platform, focusing on scientific publications related to CCUS technology research worldwide since 2000. We excluded the related abbreviations from the search query to ensure accuracy in selecting relevant literature.

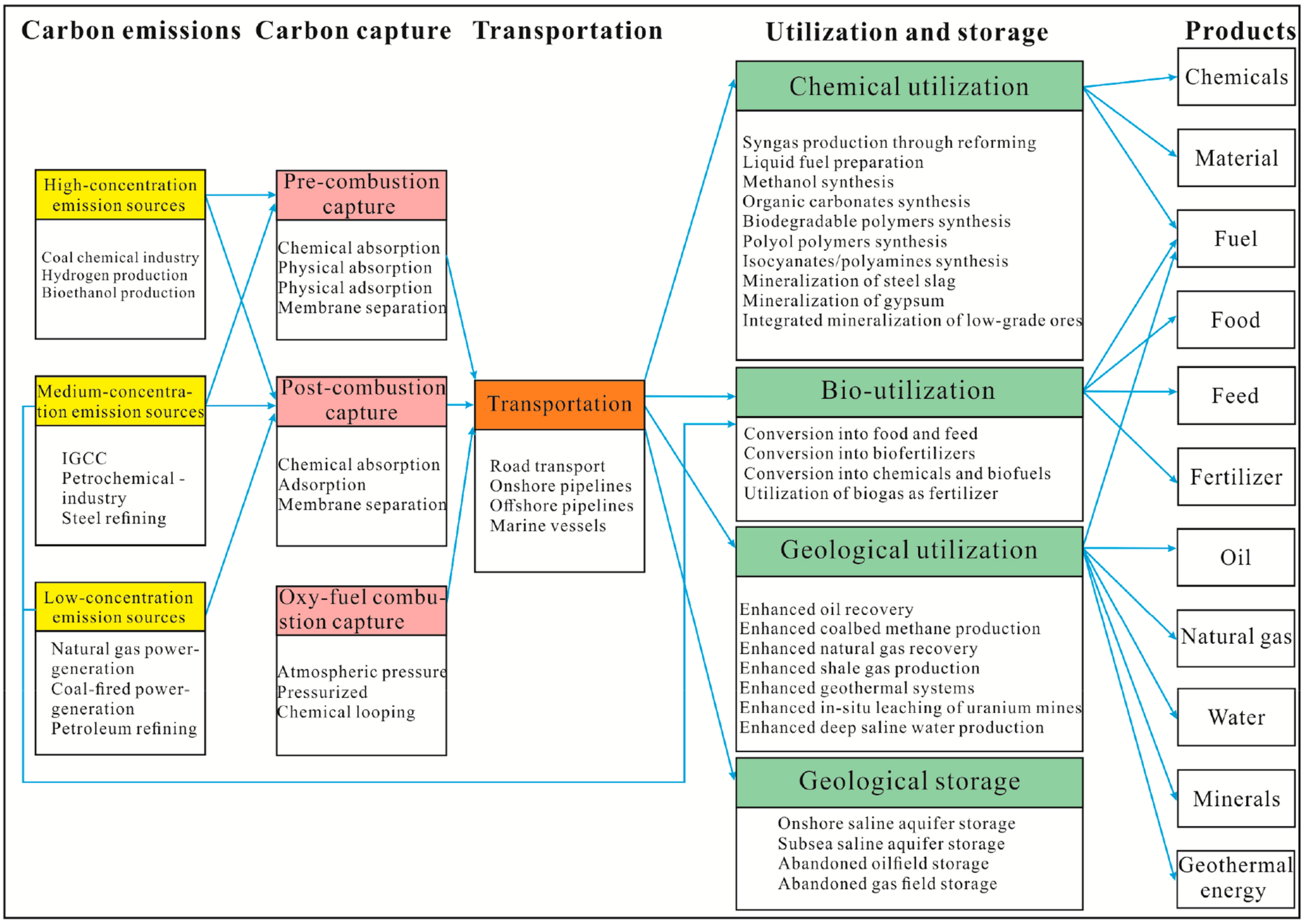

Figure 2. Schematic of CCUS technology process and classification (China CCUS Development Roadmap, 2019).

The search query was as follows: TS = ("carbon capture and storage" or "carbon capture, utilization, and storage" or "carbon capture, utilization" or "CO_2 capture, utilization, and storage" or "CO_2 capture, utilization, and sequestration" or "CO_2 capture and storage" or "carbon capture and utilization" or "CO_2 capture and utilization").[33,34] The search was conducted on July 13, 2023, and included all articles, reviews, and meeting papers, etc. Since 2007, the number of SCI papers has reached 20 393, with a rapid increase in research worldwide after 2010, making it an ongoing hot topic of discussion. In 2022, 2661 papers were published (Figure 1A). Due to the data only being collected up to July 13, 2023, it is challenging to compare the years from 2007 to 2022 directly. However, based on the current count of publications (710 papers), it can be predicted that the number of papers in 2023 has decreased somewhat but remains at a high level. Notably, Jin et al. published the first paper in 2008, addressing the technical challenges of CO_2 recovery and discussing the mechanism of combining CO_2 recovery with energy conversion. They proposed a new technological route for constructing a suitable energy network in China, providing new avenues for developing sustainable energy and environmental technologies.[35] Subsequently, China's research on CCUS technology continued to gain momentum, reaching a peak of 1039 papers in 2022 (Figure 1B).

Regarding the countries/regions contributing to published papers, scholars from as many as 150 countries/regions have contributed. China (including Taiwan) stands out with an absolute advantage of 5370 research papers, followed by the United States (4271 papers) and England (2149 papers) (Figure 1C). Among the top 10 institutions in terms of publication volume, the Chinese Academy of Sciences (930 papers), United States Department of Energy (907 papers), N8 Research Partnership (541 papers), Centre National de la Recherche Scientifique cnrs (363 papers), and Imperial College London (356 papers) rank high. Chinese Academy of Sciences and the United States Department of Energy account for 4.5% and 4.4% of the world's total publication volume, respectively. The top three institutions contribute 2378 papers, accounting for 11.7% of the total publications (Figure 1D). Chinese Academy of Sciences, United States Department of Energy, and N8 Research Partnership exhibit significantly greater research capacity and investment in CCUS technology than other institutions. Overall, the research hotspots mainly include the key technologies related to increasing oil/gas recovery (CCUS-EOR/EGR), low-carbon hydrogen production technologies coupled with CCUS, and key technologies for geological storage. Among these projects, enhancing oil and gas recovery rates through CO_2 utilization is the predominant application trajectory. Primarily targeting conventional reservoirs, these initiatives yield an approximate range of 0.1−0.6 t of crude oil per ton of CO_2 injected.

1.2. Overview of CCUS Technology. Over the past decade, CCUS technology has made significant progress across various stages of the capture, utilization, and storage chain, with new techniques providing strong support for the sustainable development (Figure 2).[36−41] CO_2 capture technology involves enriching, compressing, and purifying CO_2 to obtain high-concentration CO_2. Based on the concentration of carbon emissions, CO_2 emission sources can be categorized as high-, medium-, or low-concentration sources. The methods for CO_2 capture include precombustion capture, in-combustion capture, and postcombustion capture.[42−44] Precombustion capture techniques encompass chemical absorption, physical absorption, adsorption, and membrane separation technologies. These methods exhibit relatively lower separation difficulty and cost due to the small flue gas flow and high CO_2 partial pressure. However, they are characterized by complex processes, poor operational stability, and high requirements for gas turbines. In-combustion capture technologies mainly include oxy-fuel combustion and chemical looping combustion. Oxy-fuel combustion carbon capture technology is generally cost-effective and easily scalable, making it suitable for new coal-fired power plants. It can be further divided into atmospheric, pressurized, and chemical looping capture methods and is one of the most readily scalable and commercially viable CCUS technologies. Postcombustion capture separates CO_2 from flue gases emitted after combustion, mainly employing chemical absorption, physical absorption, and membrane separation methods.[45−48] The technology process is relatively mature, but the large gas volume, low concentration, and impurities increase separation energy consumption and costs.

Within the framework of CCUS, CO_2 utilization and storage technologies are often synergistic, encompassing geological, physical, chemical, and biological utilization methods. CO_2 geological utilization is currently the most widely promoted and economically beneficial technique. It includes CCUS-EOR and CUS-ECBM (enhanced coal bed methane) technologies.[49,50] Among them, CCUS-EOR technology has undergone large-scale engineering demonstration stages and has achieved positive application results in oilfields such as Daqing, Jilin, Jiangsu, Shengli, and Huadong Oil and Gas Company, holding dual significance in guaranteeing national energy security and protecting the ecological environment.[51−53] Physical utilization of CO_2 primarily refers to its applications in the food industry, such as producing carbonated beverages, deoxygenated water, dairy products, and food preservation. In chemical utilization, CO_2 can serve as a raw material for the synthesis of various chemical products, including urea, ammonium bicarbonate, dimethyl carbonate, polycarbonates, methane, synthesis gas, methanol, polyurethane, and salicylic acid.[54,55] In the context of biological utilization, CO_2 can promote the photosynthesis of crops, transform into food and feed, and be utilized in synthesizing pharmaceuticals, health products, and chemical raw materials, presenting extensive commercial prospects.

Regarding CO_2 storage methods, geological and ocean storage are the main approaches. Geological storage primarily involves the injection of captured CO_2 into underground spaces for permanent sequestration, reducing CO_2 emissions into the atmosphere. Ocean storage includes two main methods: dissolution and lake storage, which involve transporting CO_2 through pipelines or vessels and storing it in deep seawater or deep ocean beds.[56,57] Overall, oil and gas reservoir storage remains predominant in the short term, while saltwater formations and seawater storage are expected to become the main approaches in the medium and long-term.

2. GLOBAL PROGRESS IN CCUS TECHNOLOGY

2.1. Progress in CCUS-EOR/EGR Technology.

CCUS-EOR technology is a crucial method of geological utilization and is currently one of the more mature geological utilization technologies. The principle of CCUS-EOR lies in the favorable effects of CO_2 on crude oil, such as expanding it, reducing its viscosity, altering its density, and lowering interfacial tension. Simultaneously, CO_2 can vaporize light fractions in crude oil, facilitating gas flooding for enhanced oil recovery, improving the underground mobility of crude oil, and achieving carbon sequestration objectives (Figure 3).[8,58,59] Over the past 40 years, it has yielded positive application results, with approximately 10×10^8 t of CO_2 being injected into geological formations worldwide, effectively increasing oil recovery rates.

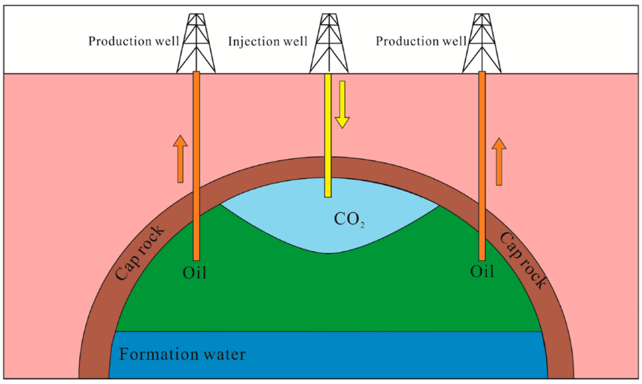

Figure 3. Schematic representation of the CCUS-EOR technology principle.

In the 1950s, the United States took the lead in researching and applying CCUS-EOR technology, and by 2018, the volume of CO_2 used for oil recovery reached 1550×10^4 t.[60,61] In the 1960s, China also began its experiments with CO_2 injection to enhance oil recovery, and by the end of 2019, it had accumulated 500×10^4 t of CO_2 injection into geological formations, resulting in a widespread increase in oil recovery rates of 3.0%−15.0%. By the end of 2020, 28 large-scale projects were operational worldwide, collectively achieving an annual CO_2 sequestration of 4×10^7 metric tons. Among them, 14 are situated in the United States, 4 in Canada, 3 in China, 2 in Norway, and 1 each in Brazil, Saudi Arabia, the United Arab Emirates, Qatar, and Australia.[62,63]

As of October 2022, China had 99 demonstration projects in operation or planned, including Sinopec's million-ton-scale CO_2 capture and storage-enhanced oil recovery demonstration project in the Shengli Oilfield, CO_2 capture and enhanced oil recovery demonstration projects in coal-fired power plants, PetroChina's CO_2-enhanced oil recovery research and demonstration project in the Jilin Oilfield, and the integrated CCUS project in Shaanxi Yanchang Petroleum.[64] Additionally, China National Offshore Oil Corporation (CNOOC) has begun planning for a multimillion-ton-scale demonstration project. In general, North America's CCUS-EOR technology and supporting process system are mature, while China is currently in the stage of industrial testing and enhancing application benefits (Table 1). However, China still faces various challenges, such as the difficulty in evaluating CO_2 flooding reservoirs in complex continental geological bodies, immature technology for expanding swept volume, incomplete layered injection processes, and high costs of corrosion prevention. Therefore, it is necessary to research the multiphase flow mechanism of CO_2 flooding in porous media, the characterization of advantages of gas flooding in strong heterogeneous reservoirs, reasonable well

Table 1. Major EOR Projects at Home and Abroad

region	oil and gas field	project name	capture/utilization method
United States	Kelly-Snyder Oilfield, Texas	SACROC	chemical absorption/EOR
United States	Citronelle Oilfield, Alabama	Citronelle	chemical absorption/EOR, Ggeological sequestration
United States		Century Plant	chemical absorption/EOR
Canada	Weyburn Oilfield	Weyburn	chemical absorption/EOR
Canada	Clive Oilfield	Clive	chemical absorption/EOR
China	Shaanxi Yanchang Petroleum	5 × 10^4 t/a CO_2 capture and demonstration project of Shaanbei coal and chemical	physical absorption/EOR
China	PetroChina Jilin Oilfield	CO_2-EOR research and demonstration project in Jilin Oilfield	enriched combustion/EOR
China	Sinopec Zhongyuan Oilfield	CO_2-EOR project in Zhongyuan Oilfield	chemical absorption/EOR
China	PetroChina Xinjiang Oilfield	Karamay Dunhua Petrochemical–Xinjiang Oilfield CO_2-EOR project	chemical absorption/EOR
China	PetroChina Changqing Oilfield	CO_2-EOR project in Changqing Oilfield	low-temperature methanol washing/EOR
China	PetroChina Daqing Oilfield	CO_2-EOR project in Daqing Oilfield	chemical and physical absorption/EOR
China	Sinopec Huadong Oil and Gas Field	comprehensive CCUS demonstration project in Huadong Oil and Gas Field	precombustion capture/EOR
China	Sinopec Qilu Petrochemical Company	Qilu Petrochemical CCUS project	precombustion capture/EOR
China	Sinopec Shengli Oilfield	CO_2 capture and enhanced oil recovery demonstration project of Shengli Oilfield coal-fired power plant	postcombustion capture/EOR
China	Sinopec Shengli Oilfield	Sinopec coal-to-gas CO_2 capture and enhanced oil recovery sequestration demonstration project	coal gasification capture/EOR
China	Sinopec Shengli Oilfield	million-ton CO_2 capture and sequestration-enhanced oil recovery demonstration project	postcombustion capture/EOR

networks and development laws, and the expansion of swept volume. Concurrently, advancing engineering demonstration projects and gradually transitioning toward large-scale and full-process projects are crucial.

The principle of CCUS-EGR technology involves injecting CO_2 into reservoirs to increase the gas permeability, generate favorable flow ratios for displacement, extend the water-free and low-water production period of edge-bottom water gas reservoirs, and enhance gas recovery through gravity segregation, among other factors (Figure 4).[65,66] China has abundant natural gas resources and multiple closures suitable for CO_2 sequestration, mainly distributed in the Ordos Basin, Sichuan Basin, Yinggehai Basin, Tarim Basin, Junggar Basin, and Bohai Bay Basin, with a sequestration capacity of approximately 304.8 × 10^8 t.

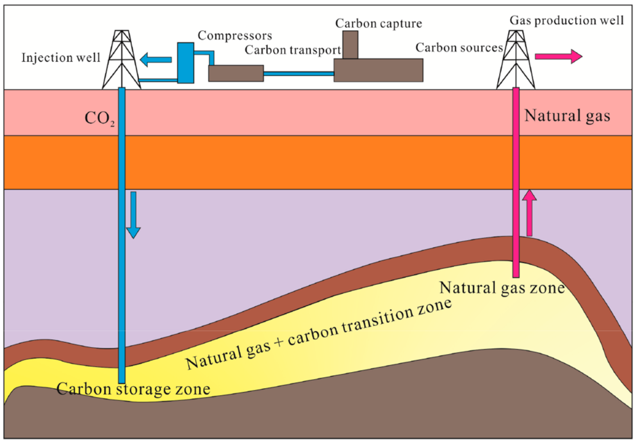

Figure 4. Schematic representation of the CCUS-EGR technology principle.

Compared to depleted oil reservoirs, natural gas reservoir closures have higher integrity and a lower risk of CO_2 leakage. Due to the higher compressibility of natural gas, the CO_2 sequestration capacity per unit volume of pore space is greater. Moreover, the differences in surface and subsurface facilities used for CO_2 injection and natural gas extraction are small, significantly reducing sequestration costs.

However, CCUS-EGR technology involves multiphase and multicomponent flow, physical and chemical processes such as CO_2–fluid–rock interactions, and other technical barriers, leading to a scarcity of global projects.[67,68] There are only a few small-scale pilot projects and mechanistic research initiatives worldwide, such as the CO_2 CRC Otway and Castor projects in Australia, the Clean project in the Altmark gas field in Germany, the Alberta project in Canada, and the K12-B project in The Netherlands. Only small-scale pilot tests in China have been conducted in the Qinshui Basin.

To promote this technology, China should intensify research efforts in areas such as predicting the behavior of multicomponent mixtures, CO_2–gas mixture control, evaluating CO_2–fluid–rock coupling effects, and assessing gas reservoir geological stability. Additionally, efforts should be made to strengthen policy support systems and establish methods and standard systems. Utilizing the gas-rich regions of the Ordos Basin and Sichuan Basin as demonstration areas for CCUS-EGR, China can enhance the overall economic benefits through large-scale industrial clusters.

2.2. Progress in Hydrogen Production Technology Coupled with CCUS. Hydrogen energy is a crucial clean energy source for the future; however, its production process is accompanied by many CO_2 emissions. Developing low-carbon hydrogen production technology through coupled CCUS is essential to achieve hydrogen's green and low-carbon utilization throughout its entire lifecycle. Hydrogen production technologies, both domestically and internationally, mainly include fossil energy-based hydrogen production, industrial byproduct

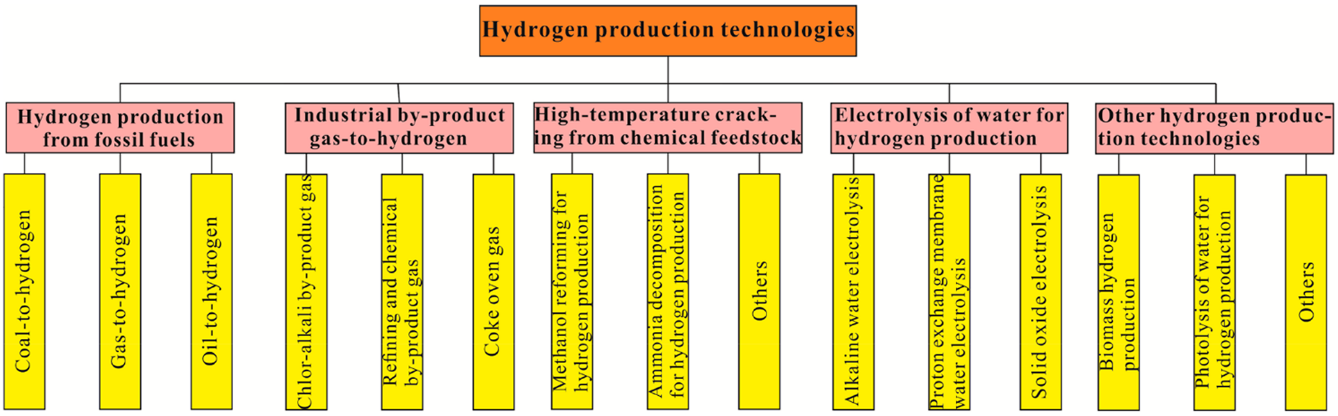

Figure 5. Major hydrogen energy technologies and classifications.

gas-based hydrogen production, high-temperature cracking of chemical raw materials for hydrogen production, water electrolysis for hydrogen production, and other hydrogen production methods, with coal and natural gas-based hydrogen production being the most prominent (Figure 5).[69,70] The current hydrogen production technologies are diverse but generally face challenges such as low conversion efficiency, poor economic feasibility, and high carbon emissions.

In 2005, the Intergovernmental Panel on Climate Change (IPCC) published a special report for accelerating the rapid development of hydrogen production technology coupled with CCUS. With the effectiveness of the Paris Agreement in 2016, its research became a focal point, leading to the emergence of various hydrogen production technologies and the exploration of their respective advantages and disadvantages.

2.2.1. Sorption-Enhanced Steam−Methane Reforming (SESMR) Hydrogen Production Technology. Traditional steam−methane reforming (SMR) hydrogen production technology consists of two main reactions:[71,72] the reforming reaction and the water−gas shift (WGS) reaction, with their respective chemical equations as follows:

$$CH_4(g) + H_2O(g) \rightleftharpoons 3H_2(g) + CO(g) \tag{1}$$

$$CO(g) + H_2O(g) \rightleftharpoons H_2(g) + CO(g) \tag{2}$$

The SESMR hydrogen production technology combines the reforming catalyst and CO_2 adsorbent, integrating both reactions into a single process.[73−75] The selection of an appropriate CO_2 adsorbent is critical for the SESMR hydrogen production technology, with the reaction equation as follows:

$$CH_4(g) + 2H_2O(g) + \sum(s) \rightleftharpoons 4H_2(g) + \sum \cdot CO_2(s) \tag{3}$$

The Σ symbol represents the solid adsorbent. CO_2 is captured by the solid adsorbent, simultaneously shifting the chemical equilibrium to the right, promoting a more complete reaction, and further enhancing the purity of H_2. The separation process of CO_2 involves the reverse reaction of adsorption, where CO_2 and the regenerated adsorbent are obtained through high-temperature calcination.[76,77] Solid adsorbents typically include calcium-based, alkali-based, and metal-oxide materials, among others. Similar to SMR, a high S/C ratio will result in a high CO conversion rate but may lead to efficiency losses. As the net moles in the reaction remain unchanged, the total pressure does not affect the CO conversion rate. However, higher pressures will result in a faster reaction rate. The WGS reaction is typically conducted in two stages: a high-temperature step (HT WGS) for faster reactions with minimized catalyst volume and a low-temperature step (LT WGS) for higher conversion rates. This approach results in a smaller adiabatic temperature rise and improved steam management while obtaining high conversion. After WGS, the syngas are cooled, and water is removed through flashing.

2.2.2. Chemical Looping Hydrogen (CLH) Production Technology. CLH technology is divided into two main categories: chemical looping combustion (CLC) and chemical looping reforming (CLR) for hydrogen production.[78−81] The CLC hydrogen production process generally consists of three steps: In the fuel reactor, metal oxides react with the fuel to produce CO_2 and H_2O (eq 4), simultaneously reducing the oxygen carrier. CO_2 and H_2O are then separated through condensation. In the steam reactor, the oxygen carrier reacts with water vapor to produce H_2 (eq 5) while partially oxidizing the oxygen carrier. The oxygen carrier enters the air reactor and undergoes complete oxidation with air (eq 6).

The CLR hydrogen production technology involves the partial oxidation reaction to produce synthesis gas ($CO + H_2$) (eq 7). The remaining processes are similar to the SESMR hydrogen production technology. In the CLH technology, the oxygen carrier plays a crucial role in the reaction, and currently, nickel-based, iron-based, manganese-based, and composite types of oxygen carriers are mainly used.

$$MO(s) + CH_4(g) \rightarrow 4M(s) + 2H_2O(g) + CO_2(g) \tag{4}$$

$$M(s) + H_2O(g) \rightarrow MO(s) + H_2(g) \tag{5}$$

$$2M(s) + O_2(g) \rightarrow 2MO(s) \tag{6}$$

$$MO(s) + CH_4(g) \rightarrow M(s) + 2H_2(g) + CO(g) \tag{7}$$

2.2.3. Underground Coal Gasification (UCG) Hydrogen Technology. China's fossil energy possesses the characteristics of being "rich in coal, low in natural gas, and poor in oil," with coal accounting for about 70% of the energy resources. Coal, as a hydrogen production feedstock, is abundant and cost-effective.[82−84] Coal gasification offers favorable reaction conditions and process control compared to coal coking. UCG, coupled with CCUS technology, is a low-carbon and clean coal hydrogen production method China has vigorously promoted in recent years. The process involves injecting gasification agents into the underground coal seam through wellbores to achieve controlled combustion with the underground coal. It undergoes a series of chemical reactions such as thermal pyrolysis, steam conversion, and carbon monoxide transformation, resulting in the recovery and purification of high-purity hydrogen and hydrogen, carbon monoxide, methane, and CO_2. CCUS technology is used to capture and utilize CO_2, which is then geologically sequestered.[85] The main reactions include partial oxidation reaction (eq 8), complete oxidation reaction (eq 9), steam conversion reaction (eq 10), carbon monoxide transformation reaction (eq 11), and methane formation reaction (eq 12).

$$2C + O_2 \rightarrow 2CO \quad (8)$$

$$C + O_2 \rightarrow CO_2 \quad (9)$$

$$C + H_2O \rightarrow CO + H_2 \quad (10)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (11)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + H_2O \quad (12)$$

Generally speaking, before 2005, SMR technology was a research hotspot and widely applied, making it the most mature and extensively used hydrogen production technology to date. After 2005, SESMR and CLC hydrogen production technologies gradually developed and underwent engineering trials, with research focused on the catalytic and adsorption effects of catalysts. UCG hydrogen production technology has a solid resource foundation in China and can be extensively applied in the thermal power industry.

2.3. Key Advancements in Geological Carbon Sequestration.

2.3.1. Evaluation of Geological Sequestration Potential.

Various underground spaces are suitable for CO_2 geological sequestration, such as depleted oil and gas reservoirs, saline aquifers, and underground cavities. Any sufficiently deep formation with enough porosity and permeability can be considered a potential sequestration site. CO_2 geological sequestration involves four types of sequestration mechanisms: structural trapping, residual gas trapping, dissolution trapping, and mineral trapping (Figure 6).[86−89] The amount of CO_2 captured through different trapping mechanisms varies over time after injection into the subsurface medium, with physical trapping initially dominating, followed by a gradual transition to chemical trapping. When a subsurface medium experiences water−rock interactions, altering the fluid chemistry and even the rock framework, changes occur in the lithology and properties of the medium, leading to the ultimate realization of mineral sequestration.[90−93] The selection of depleted gas reservoirs as potential sites for carbon storage has become a focal point in global CCS research. In recent years, researchers have been actively exploring various types of depleted gas reservoirs to assess their potential applicability and feasibility. First and foremost, there has been a strengthening of geological assessment studies, involving detailed analyses of parameters such as porosity, permeability, and caprock integrity. This helps determine which reservoirs are best suited for long-term carbon storage and how to effectively sequester injected CO_2. Furthermore, global-scale geophysical and geochemical research is continuously advancing to gain a better understanding of reservoir structures and subsurface geological features. These studies utilize advanced techniques such as seismic surveys and geophysical investigations to identify potential geological constraints and reservoir conditions. Additionally, research into the interaction between stored fluids and CO_2 within depleted gas reservoirs has gained increased importance to ensure the long-term stability of carbon storage. This includes understanding the chemical characteristics of subsurface fluids and potential reactions that may occur.

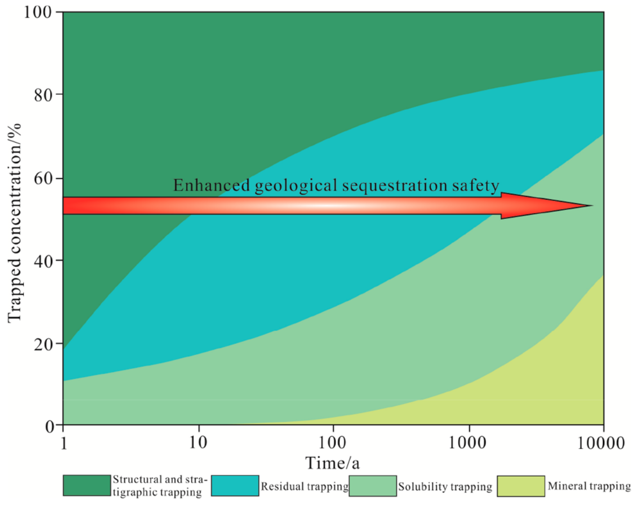

Figure 6. Illustration of carbon geological storage mechanisms.

Assessing the storage potential of oil and gas basins is currently the most realistic option for CO_2 geological storage and is crucial for achieving large-scale CCUS applications. The evaluation of CO_2 geological storage potential is typically divided into several stages, which include national/state-level screening, basin-level evaluation, site description, and site application in the regions outside of China. Various indicators such as geological characteristics of the storage formation, regional geology, assessment objectives, local protection, social health, storage safety, and environmental risks are considered in the basin-level evaluation, forming a series of evaluation indicator systems, and multiple evaluation methods for storage potential have been established.

The evaluation methods for CO_2 geological storage potential in oil and gas basins primarily include the volumetric method, storage mechanism characterization method, compressibility factor method, dimensionless parameter analysis method, and dynamic simulation method. In the early stages of storage potential evaluation and planning, institutions like the U.S. DOE and Geological Survey (USGS) mainly adopted the volumetric method.[94−97] However, using the effective storage coefficient as the main evaluation indicator in this method has resulted in inconsistent evaluation results.

The overall assessment of carbon geological storage potential in China is in its initial stages, and a unified and systematic evaluation method has not yet been established. In recent years, Chinese scholars have actively explored methods suitable for assessing CO_2 storage potential in the country. For instance, focusing on saline aquifers in oil and gas basins, a carbon storage potential evaluation method has been developed that considers geological, engineering, and economic factors as limiting conditions.[98,99] This method is designed to suit the characteristics of oil and gas basins and utilizes four scales (basin, subbasin, zone, and trap) (Figure 7A)[99] and three levels (theoretical storage capacity, engineering storage capacity, and economical storage capacity) (Figure 7B)[99] to assess carbon storage potential. Specifically, the carbon storage potential in oil and gas basins can be evaluated at four scales: basin-level, sub-basin-level, zone-level, and trap-level. The assessment can be

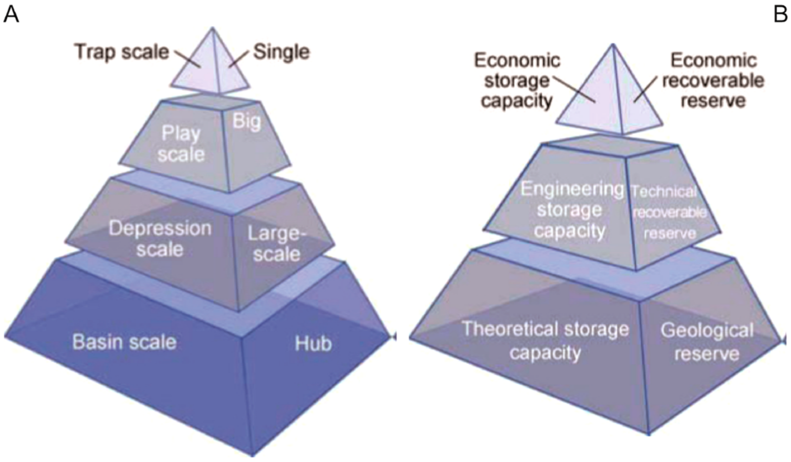

Figure 7. Schematic representation of the scale classification (A) and resource classification (B) for carbon storage potential evaluation in Chinese oil and gas basins.

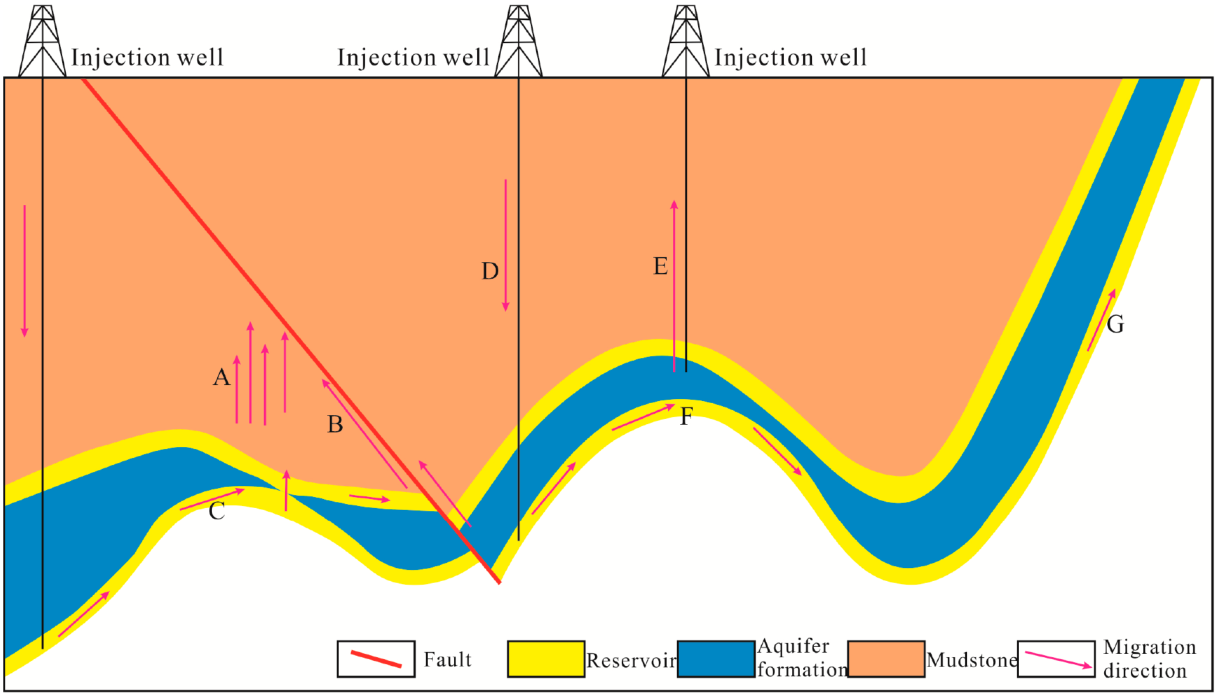

Figure 8. Illustration of CO_2 geological sequestration leakage risk. (A). Excessive pressure of injected CO_2 within the storage formation may breach the sealing caprock, enabling it to penetrate or traverse sedimentary layers. (B). Geological movements can generate numerous faults or fractures within the geological structure, facilitating the infiltration of CO_2 into adjacent layers along fault lines. (C). Sequestered CO_2 can penetrate the rock sealing layer, resulting in its leakage into underlying aquifers. (D). Injection of subsurface CO_2 elevates reservoir pressure, thereby increasing the permeability of geological faults and enhancing the likelihood of CO_2 migration along these fault lines. (E). Injected CO_2 undergoes natural dissolution at the CO_2/water interface, leading to its dissolution of CO_2 and subsequent migration from the sealing layer in various forms. (F). CO_2 injected into abandoned underground wells can lead to leakage. (G). Dissolved CO_2 migrates along the storage layer's structure and can ultimately reach the atmosphere or marine environments.

categorized into three levels: theoretical storage capacity, engineering storage capacity, and economic storage capacity.

However, the accuracy and generalizability of these methods require further validation. In conclusion, the establishment of an appropriate evaluation system and selection of indicators for CO_2 geological storage suitability, as well as the improvement of CO_2 geological storage capacity calculation methods, still require in-depth research.

2.3.2. Leakage Risk Assessment of Geological Sequestration. CCS is widely acknowledged as an effective strategy that can significantly contribute to achieving the net-zero emissions target by 2050. Despite the prerequisite of having well-defined trapping mechanisms for CO_2 geological sequestration site selection, there remains a risk of leakage due to operational errors or mechanical failures in injection wells, as well as the presence of abandoned wells, faults, and fractures that may serve as potential pathways for leakage (Figure 8).[101−103] A portion of the CO_2 sequestered within geological formations undergoes fixation through physical and chemical interactions within the sealing layers of the storage reservoir. Simultaneously, another

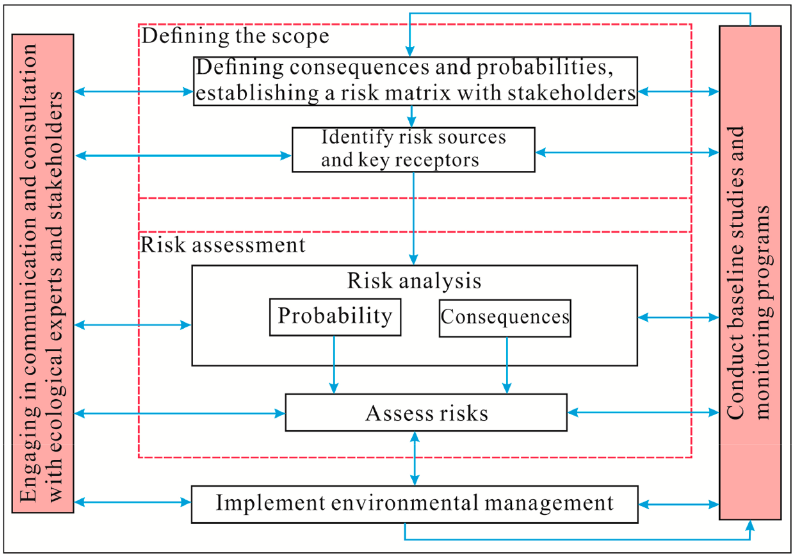

Figure 9. Illustration of the risk-based environmental assessment procedure.

fraction migrates through the geological strata, while a smaller subset permeates or escapes through geological faults, wellbore interfaces, and other localized pathways, eventually reaching soils, the atmosphere, and other environmental compartments.[103] The potential pathways for CO_2 leakage can be categorized into seven distinct trajectories, as delineated in Figures 8A–F.[103] These pathways encapsulate the intricate nature of CO_2 migration within geological formations and underscore the multifaceted potential for its release into the environment. As CO_2 injection proceeds, the risk of leakage gradually increases, reaching its peak at the end of the injection. CO_2 geological sequestration leakage risk factors can generally be categorized into wellbore and caprock.[100−102] Wellbore leakage risk is further influenced by the quality of well cementing and the corrosion of cement rings and casings. Caprock leakage risk is subject to the combined control of caprock thickness, lithology, caprock-to-reservoir thickness ratio, caprock corrosion, and storage pressure. CO_2 leakage is the most significant environmental risk associated with carbon sequestration; there are over 50 CCS injection and pilot locations worldwide, such as the Weyburn project in Canada, the Gorgon project in Australia, the Decatur project in the United States, and the Clean project in Germany, which may require long-term integrity assessments to prevent underground resource leakage or contamination.

Leakage of CO_2 from storage sites represents a primary risk associated with CCS projects. The risk of storage site leakage is particularly elevated during the initial injection into the reservoir/oil field.[104] This heightened risk primarily arises due to geological complexity and a scarcity of adequate data to comprehensively understand the consequences of CO_2 injection at the geological site. Nevertheless, the experience and knowledge gained from the initial injection can contribute to safer injections over time within the same reservoir/oil field.[105] Consequently, robust risk assessment methods are of paramount importance, especially in the early stages of carbon storage, to ensure the safety and security of the storage site, predicated on judicious site selection, comprehensive characterization, and sound decision analysis.[106] Environmental risk assessment is a process used to evaluate the probability and consequences of negative environmental impacts resulting from exposure to one or multiple risk sources. The general process includes establishing a risk assessment framework, identifying potential risk sources, identifying key receptors, assessing consequences and likelihood, and determining management measures (Figure 9).[107−110] Among them, risk identification is crucial for geological sequestration environmental assessment, and the methods for identifying geological sequestration environmental risks mainly include FEP (feature, event, and processes), FMEA (failure mode and effects analysis), ETA (event tree analysis), FTA (fault tree analysis), and others.[111,112] Qualitative risk assessment methods include risk identification and analysis based on fault leakage, wellbore failure, and seal, such as CASSIF (carbon storage scenario identification framework), SWIFT (the structured what-if technique) for qualitative risk identification and analysis, VEF (vulnerability evaluation framework) for vulnerability assessment of systems, SRF (screening and ranking framework) based on health, safety, and environment (HSE) for screening and ranking, as well as the bow-tie method for facility engineering. Quantitative risk assessment methods generally include P&R (the performance and risk) based on project performance and CO_2 leakage risk, CFA (the certification framework approach) assuming wellbore failure as the main potential leakage pathway for CCS, CO_2−PENS (predicting engineered natural systems) as a system modeling approach, and RISCS (risk interference subsurface CO_2 storage) for monetizing basin-level leakage risk and stakeholder impact.[113]

However, these methods often overlook that various risk factors in geological sequestration projects do not exist in isolation but are interconnected, leading to conflicts of interest throughout the project's lifecycle. This increases the coupling effect of different risk factors and consequently impacts the project's overall progress. Therefore, Jing et al. integrated interviews, literature analysis, and brainstorming methods to identify 46 potential risk factors that may occur throughout the lifecycle of CO_2 geological sequestration projects.[114,115] They used social network analysis to construct a risk network relationship model, clarifying the interrelationships among the risk factors in CO_2 geological sequestration projects. Based on this model, they performed overall and local parameter analysis to determine the key risk factors and proposed corresponding control measures for CO_2 geological sequestration projects.

Moreover, they identified three potential risk transmission chains based on the directed relationships among the risk factors. This approach provides a fresh perspective for carbon sequestration environmental risk assessment and contributes to the sustainable development of CCUS projects.

In addition, geochemical processes during carbon sequestration have a significant impact on carbon leakage. Generally, sandstone and carbonate reservoirs are often considered optimal geological sites due to their favorable rock physics properties, sealing integrity, and trapping mechanisms.[116,117] However, when combined with changes in geological parameters, pressure, and temperature, the geochemical interactions induced by CO_2 within these storage sites may induce leakage pathways during the injection/storage period. In the long term, these geochemical activities may result in reservoir compaction and wellbore integrity issues. These interactions are essential processes that must be understood to guarantee the long-term integrity of storage sites.[118,119] Gholami et al. summarized the major minerals (such as silicates, kaolinite, arnorthite, illite, labradorite, albite, K-feldspar, glauconite, etc.) and the geochemical reactions that could occur in CO_2 sequestration sites.[119−122] During this process, pressure and temperature play significant roles. During injection, the pressure around the injection point rises, and fractures form once the injection pressure exceeds the minimum principal stress. In the long term, regional pressure changes can alter the stress state and lead to permanent geological and mechanical issues, such as vertical uplift, faulting, and caprock integrity problems.[123−126] Proper CO_2 reservoir pressure management will be a crucial factor for the success of injection operations, especially within aquifers. Temperature is a critical parameter to consider when selecting storage sites. This is primarily because during the injection process, dry supercritical CO_2 may be at a different temperature than the reservoir, and heat exchange with the surrounding rocks can lead to thermal stress and the initiation/growth of fractures.[127−130]

Overall, various mechanisms in different storage sites can capture CO_2 in the short and long-term. However, a significant amount of free CO_2 will still interact with wellbore materials (cement), caprock, reservoirs, and faults.[120] Due to the enhanced geochemical interactions caused by pressure and temperature in storage sites, certain leakage pathways may develop.

3. PROSPECTS AND OUTLOOK FOR THE DEVELOPMENT OF CCUS TECHNOLOGY IN CHINA

CCUS technology is an integral component of our nation's strategy to achieve carbon neutrality. It can be defined as follows: it represents the sole technical choice for achieving net-zero emissions from fossil fuels; it forms a crucial technical prerequisite for thermal power participation in zero-carbon power regulation; it offers a feasible solution for deep decarbonization within challenging sectors such as steel and cement; it emerges as the primary means for sourcing nonfossil carbon materials in the future. In the context of "Dual Carbon" goals, carbon peaking, and carbon neutrality, innovative development of CCUS technology is a critical and pressing need for achieving large-scale deployment in China. This endeavor holds significant implications for China's energy security and the realization of carbon neutrality objectives. However, due to the relatively late start in China, there is still a considerable gap compared to developed countries in Europe and America. To achieve emission reduction goals, it is essential to undertake CCUS development on a large scale, focusing on areas such as technology research and development, policy support, and regulatory control.

3.1. Promoting Large-Scale Application of CCUS-EOR Technology and Actively Undertaking Key Research on CCUS-EGR. Compared to other regions globally, China possesses larger reserves of low-permeability oil reservoirs, and a significant portion of these reservoirs do not yield favorable results with water flooding development methods. Therefore, CCUS-EOR technology holds vast application prospects in China. The Bohai Bay, Songliao, Ordos, and Junggar Basins are among the areas with the greatest CCUS-EOR potential, and some demonstration projects have already been implemented.[131−134] The Ordos Basin, in particular, represents one of the most favorable and safe regions for large-scale implementation of CCUS-EOR on land, with an estimated EOR potential of approximately 37×10^8 t and a CO_2 storage capacity of up to 10×10^8 t. However, the large-scale industrial application in China still faces numerous technical and economic challenges, such as the high cost of CO_2 capture, limitations in supercritical CO_2 pipeline transportation technology, and complexities in mixed-phase flooding mechanisms and fluid flow behaviors.

Natural gas is a clean and green fossil energy source, and China has many gas reservoirs, including conventional, tight, and shale gas reservoirs, with significant untapped potential.[135] The development of CCUS-EGR can enhance gas recovery from these reservoirs. Promoting the increase in natural gas production also facilitates the demonstration of CO_2 storage technology in depleted gas reservoirs, making it significant in achieving China's "Dual Carbon" goals. However, despite attracting increased global attention and being implemented on a large commercial scale, CCUS-EGR technology encounters limitations and has seen limited significant application. Furthermore, it encounters challenges, such as the lack of unified quantitative standards for carbon emission reduction effects and difficulties determining carbon sequestration benefits. Additionally, technological bottlenecks are related to predicting multiphase behaviors in complex mixtures, evaluating the coupling effects of CO_2 with geofluids and rocks, controlling the mixture of CO_2 and natural gas, and assessing the stability of gas reservoir geological structures. Therefore, China should vigorously promote the application of CCUS-EOR technology, deepen research on barriers related to the technology, establish a comprehensive policy support system, undertake key technological research, and construct standardized methods and systems.

3.2. Promoting Progress in CCUS Engineering Demonstration Projects and Developing Comprehensive Engineering Technology. China has made significant progress through industrial demonstrations, with over 100 demonstration projects in operation or planned for construction. However, we still face challenges regarding limited CCUS, resulting in a noticeable gap between carbon neutrality's demands and the achievements of developed countries like Europe and the United States. Therefore, it is imperative to elevate CCUS technology to a strategic level and proactively deploy it to meet the demands of energy security, low-carbon transformation across industries, and high-quality economic development.

Based on this foundation, we must accelerate the development of million-ton-scale CCUS projects through technological advancements, investment, coordination, and policy support.

Additionally, deploying CCUS at a cluster level for decarbonization is an inevitable choice for achieving sustainable development, and comprehensive engineering plays a pivotal role in the scaled deployment of decarbonization industries.

Comprehensive engineering CCUS technology refers to a series of key technologies to achieve large-scale, low-energy carbon capture, efficient transportation, industrial utilization, and safe and economically effective geological storage of CO_2 from high-intensity industrial emission sources. The ultimate goal is to deploy and construct a complete chain of CCUS decarbonization industries. This comprehensive approach relies on the scientific linkage between critical CCUS technology components through source−sink matching, technical integration, and system optimization mechanisms, forming an integrated engineering system. This engineering system is continuously developed and improved in its application in various engineering scenarios. By implementing comprehensive engineering CCUS technology, we can more effectively advance the development and application, achieve carbon neutrality objectives, and actively contribute to the sustainable development of China's energy and economy.

3.3. Establishing a Robust Legal and Regulatory Framework for CCUS and Standardizing Industrial Development. Establishing a comprehensive CCUS legal framework holds significant importance as it provides clear constraints and guidance for project construction and operation, driving the development of CCUS technology within a sound legal system. This framework should consider multiple aspects to ensure systematic advancement and sustainable development. Specifically, the legal framework encompasses the following aspects:

Site Selection and Land Use Regulations: Defining the requirements and procedures for CCUS project site selection to balance rational land use and environmental protection. Development and Utilization Plan Templates: Formulating standardized project development and utilization plans, outlining project execution steps and technical requirements. Record-Keeping Management System: Establishing a robust record keeping system to comprehensively document CCUS project operational data and critical information for subsequent monitoring and evaluation. Ecological Compensation Methods and Standards: Clearly define the impact of CCUS projects on the ecological environment and develop corresponding ecological compensation measures and standards to protect the environment. Ecological Environmental Monitoring Objectives: Establishing comprehensive monitoring goals and indicators for assessing the ecological environmental impact, promptly identifying and resolving potential issues. Environmental Governance Tasks and Funding Assurance: Precisely defining the environmental governance tasks and providing necessary financial support to ensure the effective implementation of governance measures. Risk Warning Mechanism: Establishing a risk warning mechanism to promptly anticipate and respond to potential risks associated with CCUS projects. Emergency Incident Handling Plan: Formulating an emergency incident handling plan to ensure timely and effective measures are taken in unexpected circumstances. Safety Incident Liability Determination and Accountability: Clearly defining the mechanism for determining safety incident liabilities, ensuring accountability clarity.

By establishing and enhancing such a comprehensive legal and regulatory framework for CCUS, we can promote the orderly and efficient development of CCUS technology, contributing positively to our nation's carbon neutrality goals and ensuring a sustainable energy and economic future.

In addition to legal regulations, establishing a comprehensive standardization system for each stage of CCUS is also crucial, as it serves as the key to harmonious development. In the capture aspect, it is necessary to develop technical standards for various capture processes and formulate corresponding capture standards based on the nature of different gas sources to ensure an efficient and reliable carbon capture process. Regarding storage, standards need to be established for gas recovery and reinjection in CCUS-EOR projects to guarantee the stability and safety of the storage process. In monitoring, comprehensive CCUS project leakage monitoring standards should be developed to ensure effective monitoring and early warning of potential leakage risks. In assessment, it is essential to formulate CCUS project emission reduction evaluation methods, storage potential assessment standards, geological storage site assessment standards, as well as safety and environmental impact assessment methods and standards for storage areas. This will allow for a comprehensive evaluation of the environmental benefits and feasibility. By establishing a sound legal framework and standardization system, we can provide scientific guidance and effective support for the development of CCUS technology, further advancing the goals of carbon reduction and sustainable development.

3.4. Strengthening Government Financial Support and Improving the Carbon Trading System. CCUS technology is currently considered the most critical approach to carbon reduction. We can draw from the experiences of countries such as the United States and Canada to provide CCUS technology with policy support equivalent to that of renewable energy and other low-carbon clean energy technologies. Therefore, we should learn from China's experiences in exploring and developing shale gas, shale oil, and coalbed methane and expedite the formulation of tailored financial and tax incentive policies for the domestic CCUS industry.[136−138] These measures will help reduce the costs of carbon capture and storage, attracting more enterprises to participate in technological innovation and development along the CCUS industry chain.

Additionally, in December 2017, China adopted a regional carbon trading model similar to that of the United States and formally established a carbon market to improve the mechanisms, quota allocation, and carbon pricing in carbon trading. However, the current national policy support system is incomplete, lacking specific industry-wide guiding policies. This has resulted in slow progress in carbon emission trading in other sectors nationwide and, to some extent, has hindered the promotion and application of CCUS technology in China.

Therefore, we must accelerate government financial support and improve the carbon trading market, especially by establishing a comprehensive CCUS emission verification, regulatory, and carbon pricing mechanism. It is essential to construct a diverse financing system with national fiscal financing at its core, creating a favorable financial ecosystem to provide the necessary support for the healthy development of the CCUS industry. In this process, continuous improvement and optimization of policy measures are needed to ensure rapid advancement and comprehensive application, thereby promoting more significant achievements in carbon reduction and sustainable development in China.

3.5. Leveraging the Role of Online Media to Guide and Promote the Large-Scale Application of CCUS Technol-

ogy Properly. CCUS technology is paramount in carbon neutrality as a foundational element in realizing China's carbon neutrality objectives. Its significance resonates across multiple dimensions: CCUS technology serves as the exclusive technical avenue for achieving net-zero emissions stemming from fossil fuels; it represents an indispensable precondition for incorporating coal-fired power generation within the framework of zero-carbon electricity peak management; it offers a feasible technological remedy for the intricate process of decarbonizing industries such as steel and cement; and it emerges as the primary pathway for securing nonfossil carbon feedstocks in the forthcoming era.[139] Despite the profound import within research and practical implementation domains, it remains relatively less familiar to the general populace. Hence, a compelling need exists to propagate the virtues of CCUS technology proactively.

I propose fully leveraging the "Internet Plus" framework to its fullest potential, effectively utilizing various platforms and media outlets. These could encompass policy regulations, public awareness campaigns, and news media channels. Through this strategy, we can adeptly disseminate precise information concerning the goals, prospects, experiences, and accomplishments of CCUS technology across our nation. This concerted effort will direct local governments, businesses, and the general populace toward the realization that transitioning to green practices and advancing development should align with scientific, sustainable, and enduring methodologies custom-tailored to our unique national context. This approach will facilitate public comprehension that embracing sustainable development is an incremental and consistent journey rather than a rash leap, ultimately ingraining the environmental, economic, and branding advantages. Consequently, it will foster an environment conducive to constructing an ecological civilization.

4. CONCLUSIONS

This paper offers a comprehensive overview of the latest advancements and persistent challenges within CCUS technology. Encompassing areas such as CCUS-EOR/EGR, hydrogen production technology coupled with CCUS, and geological carbon sequestration, the Review sheds light on potential research trajectories within the realm of CCUS technology. Moreover, it provides astute recommendations aimed at nurturing its evolution across diverse dimensions, including technological refinement, economic viability, policy formulation, and regulatory alignment.

(1) CCUS technology is a top priority for limiting global temperature rise to 1.5 °C and is a crucial strategic choice for achieving global carbon neutrality goals. Vigorously developing CCUS technology is a key driver for promoting China's green and low-carbon development. Since 2010, global research on CCUS technology has rapidly escalated and remains a hot topic of discussion. It has primarily explored CCUS-EOR/EGR technology, hydrogen production technology coupled with CCUS, and key geological storage technologies, providing valuable guidance for the further advancement in China.

(2) CCUS-EOR is not only an essential means for achieving China's "Dual Carbon" goals but also a practical requirement for efficiently exploiting low-permeability oil and gas reservoirs. Integrating CO_2 flooding and storage is the future trend of EOR technology in China. Although the development of CCUS-EGR technology has been gradual, it holds practical significance for ensuring China's energy security, expediting the construction of a clean energy system, and driving energy transformation. Priority should be given to initiating demonstration projects in major natural gas-producing regions like the Sichuan Basin and Ordos Basin.

(3) Compared to developed countries, China has not yet established a large-scale and comprehensive long-term mechanism for CCUS technology development. There are pressing issues, such as urgent demand, lack of market mechanisms, and insufficient policy incentives. In the future, it will be essential to enhance research and development efforts, lower costs, stimulate demand, and facilitate the profound integration of the three pivotal components: technology, market, and policy. This necessitates collaborative work across fundamental research, technology development, equipment research, and integrated demonstrations. Additionally, it mandates enhancing policy, financial support, and the establishment of legal frameworks, regulations, and standard specifications to drive the sustainable growth of the CCUS technology.

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Notes

The author declares no competing financial interest.

■ ACKNOWLEDGMENTS

This study was financially supported by the Open funds of Shale Gas Evaluation and Exploitation Key Laboratory of Sichuan Province (Nos. YSK2023001 and YSK2022002) and Natural Gas Geology Key Laboratory of Sichuan Province (No. 2021trqdz05), the key R & D projects of the Deyang Science and Technology Plan (No. 2022SZ049), and the research project of Sichuan College of Architectural Technology (No. 2023KJ14).

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