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China's CCUS technology challenges and countermeasures under "double carbon" target

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Abstract: Carbon capture, utilization, and storage (CCUS) technology is pivotal for global carbon emissions reduction and plays a crucial role in ensuring China's energy security and fostering the concurrent growth of its economy. It also supports China's path towards sustainable development and ecological advancement. While significant strides have been made in CCUS technology within China, challenges persist that hinder its widespread adoption. Based on literature research and work accumulation, the current status of CCUS technology both domestically and internationally is described, and the current technical challenges and research directions that CCUS technology are pointed out. The existing research efforts have provided countermeasures to address the challenges of high energy consumption and cost of capture technologies, the need for further research on oil recovery and storage technologies, the high energy consumption and low conversion efficiency of chemical utilization technologies, and the lack of a technical system for monitoring and evaluating the safety of storage. These countermeasures are as follows: (1) Diversified integration of different carbon capture methods to achieve cost reduction at the source based on the characteristics of different emission sources; (2) Tackling multi-objective optimization techniques, coordinating and optimizing oil recovery efficiency and CO_2 storage rate; (3) Continuously developing new catalysts to accelerate the conversion reaction of CO_2 and improve conversion efficiency; (4) Fully draw on the carbon tax policies of countries such as the United States and Australia, explore fiscal and tax incentive policies suitable for China's CCUS industry, increase economic benefits, and enhance enterprise enthusiasm; (5) Establish a series of standard specifications covering all aspects of the CCUS entire chain, guide the implementation of engineering construction, and reduce enterprise risks from a standardized perspective. Through implementing these measures, the rapid development of CCUS technology in China will be promoted, and a greater contribution will be made to achieving the goal of carbon neutrality. **DOI:** 10.13809/j.cnki.cn32-1825/te.2024.01.001-en

Keywords: "double carbon"; CCUS technology; technological innovation; policy support; carbon neutrality

1 Status quo of carbon capture, utilization, and storage (CCUS) technology

CCUS is a greenhouse gas mitigation technology that significantly reduces emissions associated with the use of fossil fuels. It encompasses four major processes: CO_2 capture, utilization, and storage.

To date, CCUS technology has been widely implemented. In the capture phase, the primary approaches include post-combustion capture, pre-combustion capture, oxy-fuel combustion, and chemical-looping combustion technologies [1–2]. During the transportation phase, CO_2 can be transported via various means such as pipelines, ships, rail, or road. In the utilization and storage phase, CO_2 can be converted into high-value-added products such as cement, steel, and fertilizers, or sequestered in subsurface geological formations [3].

Major large-scale CCUS projects internationally are concentrated in North America, Europe, and Australia. Canada, one of the world's largest oil-sand producers, has implemented multiple CCUS initiatives in its oil-sand industry, which involve injecting captured CO_2 into oil sand to promote oil sand recovery and production while increasing oil recovery efficiency. In addition, the injection of CO_2 also achieves underground carbon storage, reducing greenhouse gas emissions. Examples include Suncor Energy's carbon capture and storage project, Syncrude Canada's low-emission project, and the Boundary Dam project.

In the United States, to mitigate greenhouse gas emissions and improve energy efficiency in the coal sector, the government has supported several CCUS projects. Notably, the Petra Nova project in Western Ranch oil field, Texas—a joint venture between NRG Energy and Japan's JX Nippon Oil & Energy—captures approximately 1.6 million tons of CO_2 at 99% purity every year, which is then piped to the West Ranch oil field for enhanced oil recovery.

The Australian government has implemented multiple CCUS projects in the coal industry. One of the important projects is the Gorgon project operating in Queensland, Australia, which captures CO_2 generated during liquefied natural gas production and injects it into underground rock formations of seabed to reduce greenhouse gas emissions. It can store over 1.6×10^6 tons of CO_2 annually. This project has made a significant contribution to Australia's sustainable development goals.

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In Europe, the North Sea region—one of the world's major oil and gas areas—hosts several CCUS deployments, such as Norway's Snohvit project, which captures approximately 700,000 t of CO_2 each year, thereby supporting the sustainable development of the North Sea region in Europe.

Currently, China has launched numerous CCUS demonstration projects. For instance, Sinopec has launched the first million-ton CCUS project in China—the Qilu Petrochemical–Shengli Oilfield CCUS collaborative project. In this project, with the company's upstream–downstream integration fully leveraged, the CO_2 captured by Qilu Petrochemical is transported to Shengli Oilfield for injection into the formation for oil recovery and storage, thus turning waste into wealth. It can reduce CO_2 emissions by 1×10^6 tons per year, equivalent to the effect of planting nearly 9×10^6 trees. Besides, Sinopec Nanjing Chemical Industries Co., Ltd. (hereinafter referred to as "Nanhua"), also a leader in the field of CCSU technology in China, boasts domestically leading and internationally advanced CO_2 capture technology that enjoys a wide range of application, including traditional synthesis gas, natural gas, refinery gas, EO/EG (ethylene oxide/ethylene glycol) recycle gas, Fischer–Tropsch (F-T) synthesized recycle gas, various flue gases, blast furnace gas, and kiln gas. At present, there are CO_2 capture facilities with an annual capacity of 3.5×10^5 t in four phases in the CCUS demonstration base jointly built by Liquid Carbon Company, East China Petroleum Bureau, Sinopec and Nanhua (Fig. 2).

As one of the largest coal enterprises in China, China Shenhua Energy Co., Ltd. has implemented multiple CCUS projects in coal mining and combustion processes. It captured and stored CO_2 in multiple mining areas in Inner Mongolia, Xinjiang, and other regions, reducing greenhouse gas emissions while improving the safety of mining areas.

SDIC Power has implemented carbon capture and storage projects at multiple power plants in Shanghai, Hebei, and other places, reducing greenhouse gas emissions in the power industry by capturing and storing the CO_2 generated by power plants.

According to the report *Global Status of CCS 2022* (CCS means carbon capture and storage), the global CCUS industry is exhibiting a steady growth trend. By 2022, there were a total of 196 CCUS commercial facilities worldwide with a CO_2 capture capacity of 2.4×10^8 t/a. The CCUS technology system is undergoing continuous refinement and diversification. In terms of CO_2 capture, post-combustion chemical absorption technology and pre-combustion physical absorption technologies have been put into commercial operation after engineering demonstrations. Ongoing research and development efforts are focused on emerging techniques such as chemical absorption based on novel absorbents and chemical adsorption methods. In terms of CO_2 transportation, pipeline networks have reached a scale exceeding one million tons per year, with pipeline pressures advancing into the supercritical range. These developments are enhancing the economic viability of CO_2 transport. Regarding CO_2 utilization, the field is gradually evolving beyond enhanced oil recovery (CO_2-EOR) toward chemical and biological valorization. This transition aims to enable green carbon utilization pathways such as synthesis of high-value chemicals and bioconversion of CO_2 into bio-based products.

2 Challenges

2.1 Expensive CCUS technology

2.1.1 High capture cost

The most mature CO_2 capture technology currently in use is the amine-based absorption method [4]. Although this approach is well-established and technically stable, it involves significant consumption of amine solvents and energy (primarily steam), which results in relatively high operational costs [5–7].

Amines act as chemical absorbents that react with CO_2 during the capture process. However, these solvents are subject to degradation and volatilization losses, both of which not only increase the cost of CO_2 capture but also adversely affect the overall capture efficiency. Under current technological conditions, approximately 0.5–1.0 kg of amine solvent is consumed for every ton of CO_2 captured.

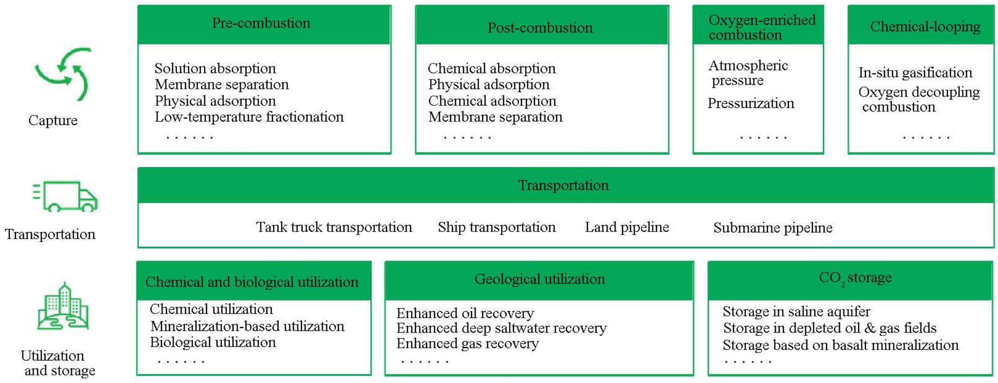


Fig. 1 Schematic diagram of CCUS technology chain

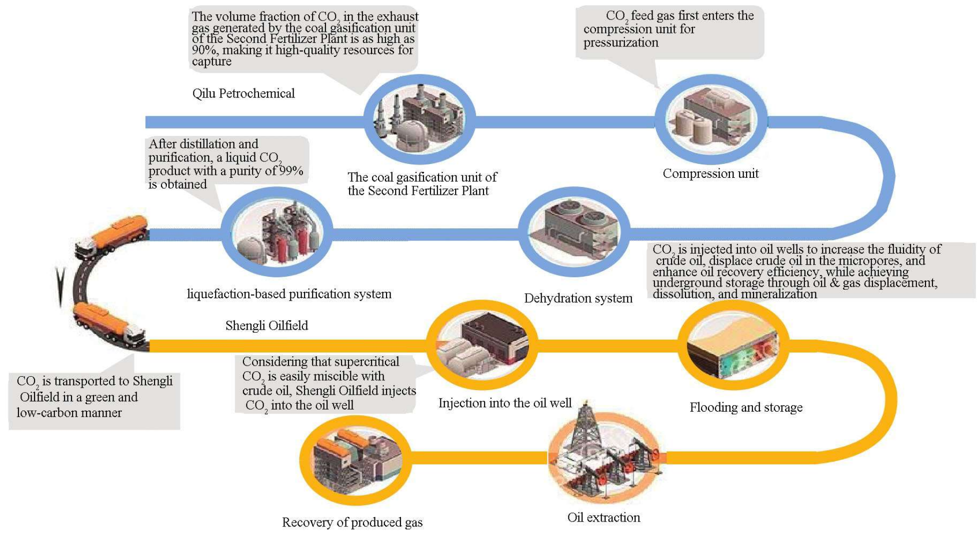
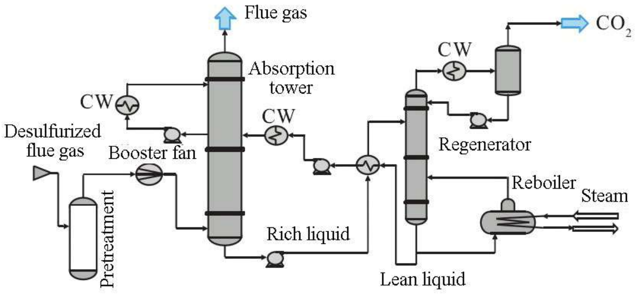


Fig. 2 Process of Sinopec Qilu Petrochemical–Shengli Oilfield CCUS collaborative project

The regeneration process following CO_2 capture also demands substantial thermal energy in the form of steam. During this stage, the CO_2-rich solvent must be heated to release the absorbed CO_2, enabling solvent reuse. This regeneration step requires roughly 1.4 t of steam per 1 t of CO_2 captured. Assuming a steam cost of CNY 100/t, the regeneration energy cost alone amounts to approximately CNY 140/t (Fig. 3).



Note: CW refers to the cold water system.

Fig. 3 Schematic diagram of typical chemical absorption process flow

2.1.2 High transportation and storage costs

In the CO_2 transportation stage, three primary methods are commonly employed: transport by tank trucks, pipelines, and ships. However, regardless of the mode of transport, CO_2 delivery is associated with relatively high costs. It is estimated that the cost of transporting CO_2 over a distance of 100 km ranges from CNY 80 to 120 per ton. When safety and environmental considerations are factored in, the overall transportation cost may increase further.

CO_2 storage can be broadly categorized into onshore (terrestrial) and offshore (marine) sequestration, depending on the storage location. Onshore storage typically involves injecting CO_2 into deep saline aquifers or depleted oil and gas reservoirs. This approach requires extensive geological surveying and complex engineering design, leading to high implementation costs (Fig. 4). Offshore storage involves sequestering CO_2 in deep-sea formations. While it reduces the risk of geological leakage, it demands offshore construction and equipment installation, posing significant technical challenges and further elevating costs. The estimated cost of CO_2 storage ranges from CNY 50 to 100 per ton. In addition to economic considerations, CO_2 storage presents several technical challenges and environmental risks. For instance, CO_2 may leak from subsurface formations, posing potential threats to both the environment and human health. Moreover, CO_2 can react with subsurface water and geological formations. Reactions between CO_2 and formation water may lead to the dissolution of calcite and minor precipitation of dolomite, potentially causing the destruction of geological structures and causing subsurface contamination.

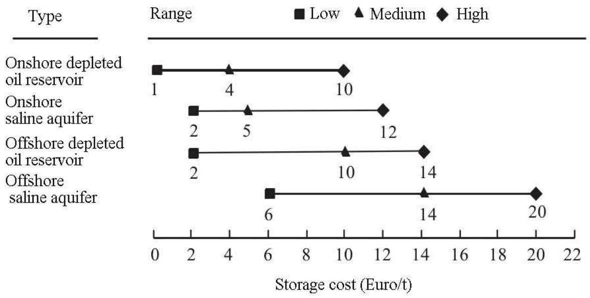


Fig. 4 CO_2 storage cost

2.2 Inadequate technological maturity

Although CCUS technologies have achieved notable progress, they remain insufficient to meet the demands of large-scale deployment.

2.2.1 Carbon capture technology

Globally, first-generation post-combustion capture using chemical absorption remains the most widely implemented method and is currently in the stage of large-scale demonstration and application. However, second- and third-generation technologies—such as novel membrane separation, advanced absorption (e.g., ionic liquid and phase-change solvents), adsorption, pressurized oxy-fuel combustion, and chemical looping combustion—are still under various stages of development and have yet to reach full technological maturity [8–11]. Nevertheless, these emerging technologies are expected to move from laboratory to practical deployment, enabling parallel development of diversified technological pathways.

2.2.2 Carbon utilization technology

Current efforts focus on synthesizing syngas and methanol from CO_2 via conventional catalytic or electrochemical methods. The catalytic approach faces challenges in terms of catalyst activity, selectivity, and stability [12–13], while the electrochemical route—though operable under ambient conditions—must overcome issues such as high energy consumption and electrode materials [14–16]. CO_2 is also used in the synthesis of organic carbonates, which serve as solvents in battery electrolytes [17–18], and in mineralization with steel slag or carbide slag to produce calcium carbonate. These technologies are predominantly at the demonstration stage and require further research and optimization to achieve industrial-scale implementation [19–25].

2.2.3 CO_2 flooding

The application of CO_2 flooding is confronted by a series of complex technical challenges [26–30]. For instance, Chinese oil reservoirs exhibit diverse geological characteristics and varying development statuses, necessitating a thorough assessment to identify those suitable forCO_2 injection. Most crude oil in China is heavy and viscous, with high reservoir temperatures, resulting in elevated miscibility pressures with CO_2 that are difficult to achieve under formation pressure conditions. Improvements in miscibility conditions are essential for enhancing CO_2-EOR efficiency. Compared to marine reservoirs in the USA, China’s continental reservoirs tend to be more heterogeneous. Some low-permeability reservoirs exhibit dynamic fracture development, requiring careful consideration of increasing the swept volume of CO_2 and reducing ineffective CO_2 injection when implementing CO_2 flooding technology. These issues must be addressed through tailored technical solutions based on the geological and operational conditions of specific fields.

2.3 Low market acceptance

The high cost and insufficient technological maturity contribute to the limited market acceptance of CCUS. Major cost components include capital investment, operational and maintenance expenditures, and expenses associated with CO_2 capture and transport. These costs diminish the economic competitiveness of CCUS technologies. In industries with widespread and large-scale emissions—such as power generation, steel, cement, and chemicals—the substantial investment required hinders proactive adoption by enterprises. Furthermore, the lack of robust policy support and regulatory frameworks restricts the application and development of CCUS in many regions.

3 Strategic measures

To address the challenges of high costs, technological immaturity, and low market acceptance currently facing CCUS technologies, future development must focus on technological innovation and policy intervention. These efforts aim to enhance the economic viability and reliability of CCUS, thereby enabling large-scale adoption.

3.1 Technological innovation

3.1.1 Capture technology

One priority is the development of advanced carbon capture technologies to reduce costs and enhance efficiency.

1) Development of high-capacity, low-energy, and cost-effective absorbents

The USA Department of Energy (DOE) has supported various research institutions in advancing CO_2 capture using ionic liquids. For example, the National Energy Technology Laboratory (NETL) has investigated multiple ionic liquid absorbents, one of which—an imide-based ionic liquid absorbent—exhibited a CO_2 absorption capacity of up to 1.65 mol/mol under experimental conditions. The University of California, Los Angeles (UCLA) also conducted research on CO_2 capture by ionic liquid method and successfully developed an ionic liquid absorbent with high absorption capacity and reaction rate.

In China, institutions such as the Institute of Process Engineering, Chinese Academy of Sciences (CAS), the Technical Institute of Physics and Chemistry, CAS, and East China Normal University have also been conducting research on ionic liquid-based CO_2 capture. These efforts involve the design of novel ionic liquid absorbents, optimization of absorption processes, and investigation on reaction mechanisms to enhance capture performance. Notably, the Institute of Process Engineering, CAS, has developed a functionalized ionic liquid absorbent with outstanding performance.

2) Development of low-energy, simple, and cost-effective membrane separation technologies

Several research institutions and companies—such as Tianjin University, Jiuzhang Membrane Technology Co., Ltd. (Shandong), Dalian Institute of Chemical Physics, CAS, and Sinopec Nanjing Chemical Industries Co., Ltd.—have achieved significant progress in membrane-based CO_2 capture. As the lead unit of a national key R&D program under China's 13th Five-Year Plan, Tianjin University collaborated with the aforementioned institutions and companies to develop a world-leading membrane-based CO_2 capture technology chain. A 50,000 Nm^3/d membrane separation-based carbon capture industrial demonstration facility was constructed at the Power Department of Nanhua, achieving a CO_2 capture rate of no less than 90% and a product gas CO_2 concentration of at least 95%.

3) Development of high-capacity, low-energy adsorption technologies

At present, the publicly reported chemical adsorption pilot and industrial test projects mostly adopt calcium oxide, alkali carbonate, and solid amine adsorption materials to achieve CO_2 capture and separation (Table 2). For example, in 2017, Kawasaki, Japan, established a 1,000-ton mobile bed solid amine adsorption facility with mesoporous silicon foam-loaded modified TEPA as the adsorption material, which boasts a capture rate of 93%, a purity of 98%, and a comprehensive energy consumption of 1.5 GJ/t. ADA Co., USA, has established a 1 MW double fluidized bed solid amine adsorption facility, achieving a CO_2 capture rate of over 90% in coal-fired flue gas. In 2019, Guohua Power Jinneng Power Plant of China Energy Investment Corporation Co., Ltd. (CHN Energy) started construction of a 1,000 t/a CO_2 fluidized bed decarbonization system based on solid amine adsorbent, capturing CO_2 with a comprehensive energy consumption of 2.2 GJ/t. To date, pilot- and industrial-scale demonstrations of chemical adsorption for CO_2 capture have predominantly utilized calcium oxide, alkali metal carbonates, and solid amine-based adsorbents (Table 2). For example, in 2017, Kawasaki, Japan, established a pilot-scale moving-bed adsorption system with a capacity of several thousand tons, employing mesoporous silica foam supported with modified tetraethylenepentamine (TEPA) as the adsorbent. This system achieved a CO_2 capture rate of 93% and a product purity of 98%, with a total energy consumption of 1.5 GJ/t. In USA, ADA Co. developed a 1 MW dual fluidized-bed system using solid amine adsorbents, which demonstrated a CO_2 capture rate exceeding 90% from coal-fired flue gas. In 2019, CHN ENERGY Investment Group Co., Ltd. initiated the construction of a 1,000 t/a fluidized-bed decarbonization system at the Jinneng Power Plant (a subsidiary of Guohua Power), also based on solid amine adsorbents. The system reported a total energy consumption of 2.2 GJ/t.

In addition, optimization of process configurations—such as the adoption of advanced steam compression refrigeration and cryogenic cooling technologies—as well as the enhancement of heat transfer techniques (e.g., improving the thermal and thermodynamic efficiency of heat exchangers) can further contribute to the reduction of CO_2 capture costs and the improvement of capture efficiency (Table 3).

Table 1 Project information on membrane separation method for capturing CO_2 in flue gas [34]

Membrane material	Test institution	Country	Test scale/(Nm^3/d)	Source of flue gas	Completed year
Polaris®	MTR	US	86 000.00	Gas-fired power plant	2014
PolyActive®	Helmholtz-Zentrum Geesthacht	Germany	1 200.00	Coal-fired power plant	2015
PVAm material	NTNU	Norway	0.96	Cement plant	2016
Ultrason®	NCCC	US	1.50	Coal-fired power plant	2017
Polaris®	China Resources Haifeng	China	86 000.00	Coal-fired power plant	2019
PVAm material	Tianjin University	China	50 000.00	Coal-fired power plant	2021

Note: MTR stands for Membrane Technology and Research, Inc., Helmholtz-Zentrum Geesthacht for Helmholtz Coastal Research Center, NTNU for Norwegian University of Science and Technology, and NCCC for the National Carbon Capture Center, USA.

Table 2 International CO_2 capture projects after chemical adsorption combustion [34]

Overview of project	Source of gas	Adsorbing material	Capture scale/MW	CO_2 capture rate/%	Main implementing agency
Caoling double circulating fluidized bed in 2009	Coal fired flue gas	CaO	1.70	>90	National Institute for Coal Research (INCAR), Spanish National Research Council (CSIC)
Entrained-flow bed + rotary kiln in USA in 2010	Coal fired flue gas	CaO	0.12	>90	The Ohio State University
Transport bed + bubbling bed in Republic of Korea in 2012	Coal fired flue gas	K_2CO_3	10.00	>80	Korea Institute of Energy Research
Double circulating fluidized bed in German in 2012	Synthetic flue gas	CaO	1.00	90 – 92	Technische Universität Darmstadt
Double circulating fluidized bed in USA in 2019	Coal fired flue gas	Solid amine	1.00	90	ADA Co.

Table 3 Evaluation on carbon capture technology [34]

Capture technology	Industrial costs							
	Status quo				2030			
	Heat consumption (GJ/t)	Electricity consumption [(kW·h)/t]	Equipment investment (CNY/t)	Total cost (CNY/t)	Heat consumption (GJ/t)	Electricity consumption [(kW·h)/t]	Equipment investment (CNY/t)	Total cost (CNY/t)
Post-combustion chemisorption	2.8	75	40	270	2.2	65	40	220
Post-combustion chemical adsorption	2.0	60	240	400	1.8	50	120	270
Post-combustion physical adsorption	2.1	80	150	330	1.9	70	120	280
Post-combustion membrane separation	0	450	150	310	0	250	120	210
Oxygen-enriched combustion	0	380	240	380	0	270	120	220
Chemical-looping combustion							80	80

Secondly, carbon capture technologies should be tailored to the characteristics of different emission sources to enable diversified technological pathways [31]. For instance, in the power sector, post-combustion capture combined with chemical absorption (e.g., membrane separation or physical adsorption) should be further developed. In industrial processes that generate CO_2 emissions—such as refinery gas decarburation, natural gas decarburation, and blast furnace gas decarbonization—chemical absorption or pressure swing adsorption may be applied accordingly. In the transportation sector, three-way catalytic converters can be used to capture and recover CO_2 from vehicle exhaust. In aerospace, technologies such as fuel cells can be adopted to replace conventional jet engines, thereby reducing carbon emissions. In the construction industry, the development and deployment of direct air capture (DAC) technologies should be accelerated.

3.1.2 Transportation technologies

The development of CO_2 transport technologies should focus on enhancing transport efficiency, improving safety, reducing costs, and minimizing environmental impacts. In terms of pipeline materials, high-strength, corrosion-resistant, and lightweight materials should be developed to increase transport efficiency and ensure safety. From the perspective of transport processes and technologies, advanced fluid dynamics and novel pumping systems should be employed to optimize flow performance. In safety control and monitoring, state-of-the-art sensors and real-time monitoring systems should be deployed to track pipeline conditions and detect leaks. Additionally, renewable energy utilization—such as the installation of solar power systems along pipeline corridors—can be used to meet part of the energy demand during CO_2 transport [32–33].

3.1.3 Utilization technologies

The conversion of CO_2 into high-value carbon-based materials represents a promising direction. This includes the production of carbon nanotubes and graphene, which can be applied in lithium battery conductive pastes, conductive plastics, and anti-corrosion coatings. Another key approach is the integration of solar energy or other renewable sources to enhance CO_2 conversion efficiency. Continuous development of advanced catalysts is essential for accelerating CO_2 conversion reactions, improving conversion efficiency, and reducing costs [35].

3.1.4 Flooding technology

The development of CO_2 flooding technologies should prioritize maximizing recovery efficiency and economic viability [27]. For low-permeability reservoirs characterized by deep burial, poor physical properties, and low resource quality, efforts should focus on lowering the minimum miscibility pressure and developing rational exploitation strategies. Key controlling factors for CO_2 flooding performance—such as well pattern/well spacing, fracturing strategies, reservoir heterogeneity, and pressure maintenance—must be evaluated. Optimization should be carried out in areas such as well pattern deployment, pressure control, injection–production coupling, and timing of CO_2 injection to maximize oil recovery. For medium- and high-permeability reservoirs transitioning from long-term water flooding to gas injection, issues such as CO_2 breakthrough and corrosion are prominent. In this context, research should focus on the mass transfer mechanism between CO_2 and crude oil under high water content, the development of foam-assisted CO_2 flooding, CO_2 thickening technologies, and intelligent injection–production adjustment, to increase injecting efficiency of CO_2. Low-cost anti-corrosion processes are also crucial for reducing overall development costs. Expanding the application of CO_2 flooding to low-permeability and geologically complex reservoirs and establishing industrial-scale CCUS demonstration projects will be essential. CO_2 flooding technology is expected to become a widely adopted method for improving the development efficiency of oil fields in China [28–30].

3.1.5 Storage technologies

Efforts in CO_2 storage should focus on increasing storage efficiency and mitigating storage risks [26]. The selection and application of storage technologies must be context-specific and need-specific to ensure optimal outcomes. For geological storage, research should consider site-specific geological conditions and environmental factors, including options such as deep saline aquifer storage and depleted oil and gas reservoir storage. Engineering applications and demonstration projects should be scaled up to improve performance and safety. For chemical storage, emphasis should be placed on catalyst selection, process optimization, and reaction mechanism studies. For physical storage, developments should target compression technology optimization and the design and fabrication of storage vessels. Additionally, integrated CCUS systems—encompassing optimized capture, diversified utilization pathways, and matched storage strategies—should be strengthened.

3.2 Policy support

Enhancing government support for CCUS technologies is essential to improving market acceptance.

Policy measures such as financial subsidies, tax incentives, and the establishment of dedicated government funds can increase investment in CCUS R&D and demonstration projects. Governments should also encourage financial institutions to enhance support for the CCUS industry. Specific tax relief policies—such as reductions in corporate income tax and value-added tax for CCUS projects—can lower project costs and incentivize corporate adoption of CCUS technologies (Table 4).

Table 4 Evaluation on carbon utilization technology [34]

	Technical name	Carbon emission reduction potential in 2030/10^4 t
Chemical conversion of CO_2 to chemicals	CO_2–methane reform for synthesis gas	2 000 – 3 000
	CO_2 cracking for liquid fuel from carbon monoxide	30 – 100
	CO_2 hydrogenation for methanol synthesis	4 800 – 7 200
	CO_2 hydrogenation for alkene	250 – 370
	CO_2 photoelectrocatalytic conversion	15 – 35
	CO_2-based synthesis of organic carbonates	350 – 500
	CO_2-based synthesis of biodegradable polymer materials	30 – 60
	CO_2-based synthesis of isocyanates/ polyurethanes	350 – 400
	CO_2-based polycarbonate (PC) synthesis technology	25 – 35
CO_2 mineralization technology	Steel slag-based CO_2 mineralization	100 – 150
	Phosphogypsum-based CO_2 mineralization technology	100 – 150
	Potassium feldspar processing coupled with CO_2 mineralization	20 – 30
	CO_2-based mineralization curing for concrete	4 000 – 4 500

The state will establish and improve the CCUS standard system, including technical specifications, equipment testing, and storage site standards, to achieve more standardized and operable CCUS technology, thus promoting the development of the CCUS industry [36]. In addition, further efforts will be made to strengthen the management and operation of carbon assets, establish a sound carbon management system, and work towards scientific and standardized carbon management by strengthening related aspects such as carbon trading, monitoring, and auditing. The government is continuously advancing the establishment and refinement of a standardized CCUS regulatory system, including technical guidelines, equipment testing protocols, and site selection criteria for CO_2 storage. These efforts aim to enhance the standardization and operability of CCUS technologies and facilitate the development of the CCUS industry [36]. Additionally, further strengthening of carbon asset management is essential. A comprehensive carbon management system should be developed through the enhancement of carbon trading, carbon monitoring, and carbon auditing, thereby promoting the scientific and systematic governance of carbon emissions.

4 Conclusions

1) Under the “double carbon” goals (carbon peaking and carbon neutrality), China’s CCUS technologies have developed rapidly. However, significant challenges remain, including high implementation costs, a lack of effective commercial models, and insufficient incentive and regulatory measures. These barriers continue to impede the large-scale commercial deployment of CCUS.

2) To promote the development and application of CCUS technologies, it is necessary to establish a comprehensive, full-chain CCUS technology R&D platform. Emphasis should be placed on the development of low-cost, low-energy-consumption technologies across all stages of the CCUS chain. In parallel, early-stage deployment of cutting-edge and potentially disruptive CCUS technologies should be supported to enhance technological maturity and market competitiveness, ultimately enabling wide-scale and sustainable global deployment.

3) Developing a robust standards system, along with incentive mechanisms, laws and regulations, industrial policies, and business modes tailored to China’s national conditions, will play a pivotal role in supporting the advancement and widespread adoption of CCUS technologies.

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