CHINA DECARBORNIZATION MARKET REPORT 2:

CCUS MARKET OVERVIEW AND U.S.-CHINA COLLABORATION

Innovation Center for Energy and Transportation

U.S.-China Cleantech Center

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We express our gratitude to the U.S. Department of Commerce's International Trade Administration (ITA) for providing funding support for this report. This is the second report of a four-part series of in-depth research into China's decarbonization market. This report provides a comprehensive analysis of the current state of China's Carbon Capture, Utilization, and Storage (CCUS) market, including its market potential, policy support, industry need, technological advancement, and project progress. Furthermore, potential opportunities for collaboration between China and the U.S. in this field are explored.

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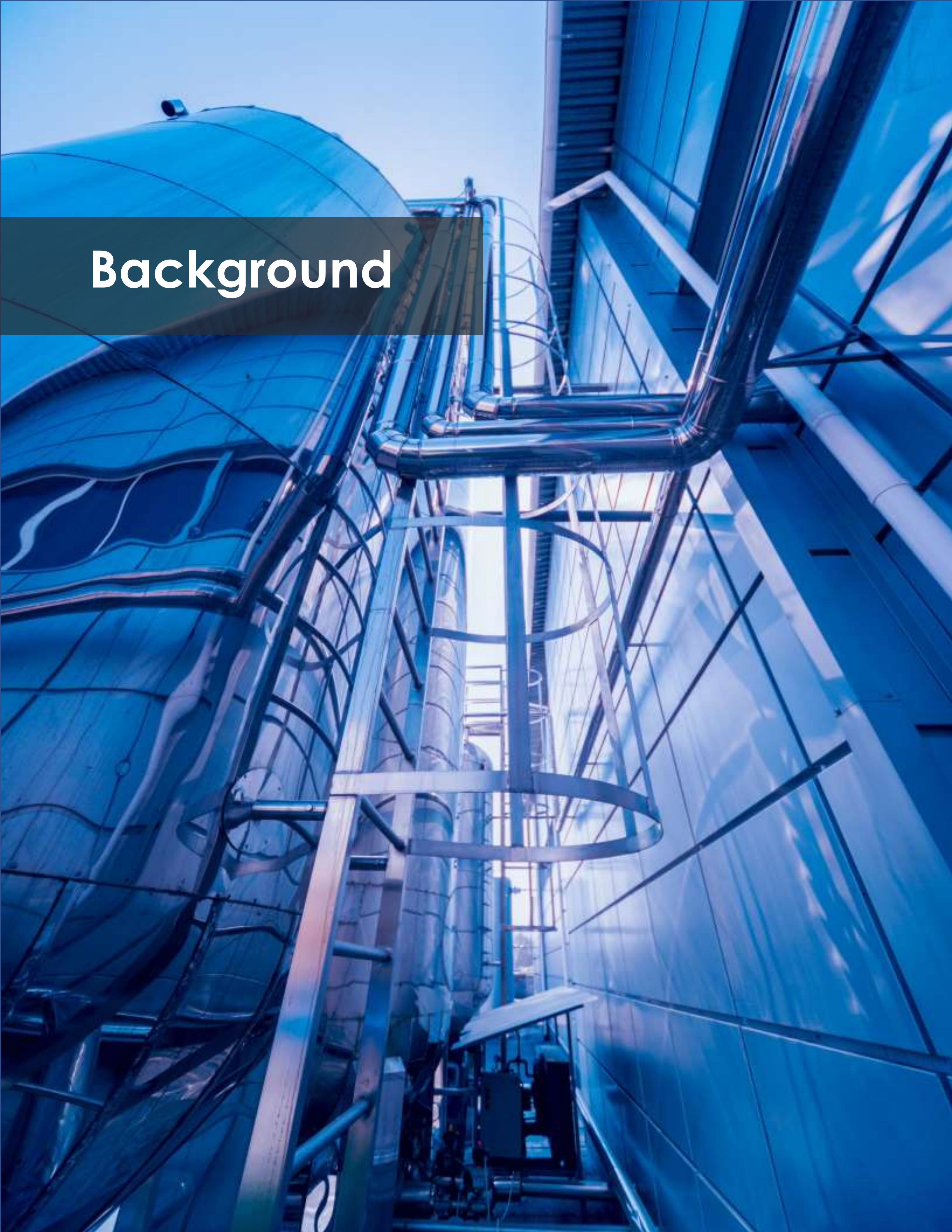
Background



1. Background

The increase in global greenhouse gas emissions has caused the greenhouse effect to intensify, leading to a rise in global temperatures. Human-generated carbon dioxide emissions are responsible for 63% of the overall rise in global temperatures, which poses a significant risk of severe and irreversible consequences for both individuals and ecosystems worldwide. The potential impacts include rising sea levels and increased frequency of extreme weather conditions. Dramatically reducing carbon dioxide emissions is crucial for mitigating these risks. Carbon Capture, Utilization, and Storage (CCUS) is a leading technology that enables large-scale carbon abatement. It involves capturing carbon dioxide (CO_2) emissions generated from fossil fuel-based power generation and industrial processes and either storing them deep underground or repurposing them for other uses. This technology has gained significant attention as a promising solution for climate mitigation.

1.1 CCUS Definition

CCUS stands for Carbon Capture, Utilization, and Storage. It is a set of technologies and processes designed to mitigate climate change by capturing CO_2 emissions from various sources, utilizing or repurposing the captured CO_2, and storing it to prevent it from being released into the atmosphere.

Carbon capture (CC) refers to the process of removing CO_2 from industrial processes, energy combustion, or atmospheric extractions. This process usually involves the pre-combustion capture, post-combustion capture, oxyfuel combustion, and chemical looping capture. If the captured carbon is not utilized on-site, it is transported to utilization or storage sites using various transportation modes such as tank truck transportation, ship transportation, or pipeline transportation.

Once the captured carbon is either on-site or transported to a desired location, it can be utilized through industrial processes to either enhance resource extractions or produce consumer products such as plastics. Based on different techniques, the utilization process can be classified into geological, chemical, and biological utilization. Geological utilization of carbon dioxide involves injecting CO_2 into the ground to enhance energy production and facilitate resource extraction, such as increasing oil and natural gas recovery rates, or extracting various resources such

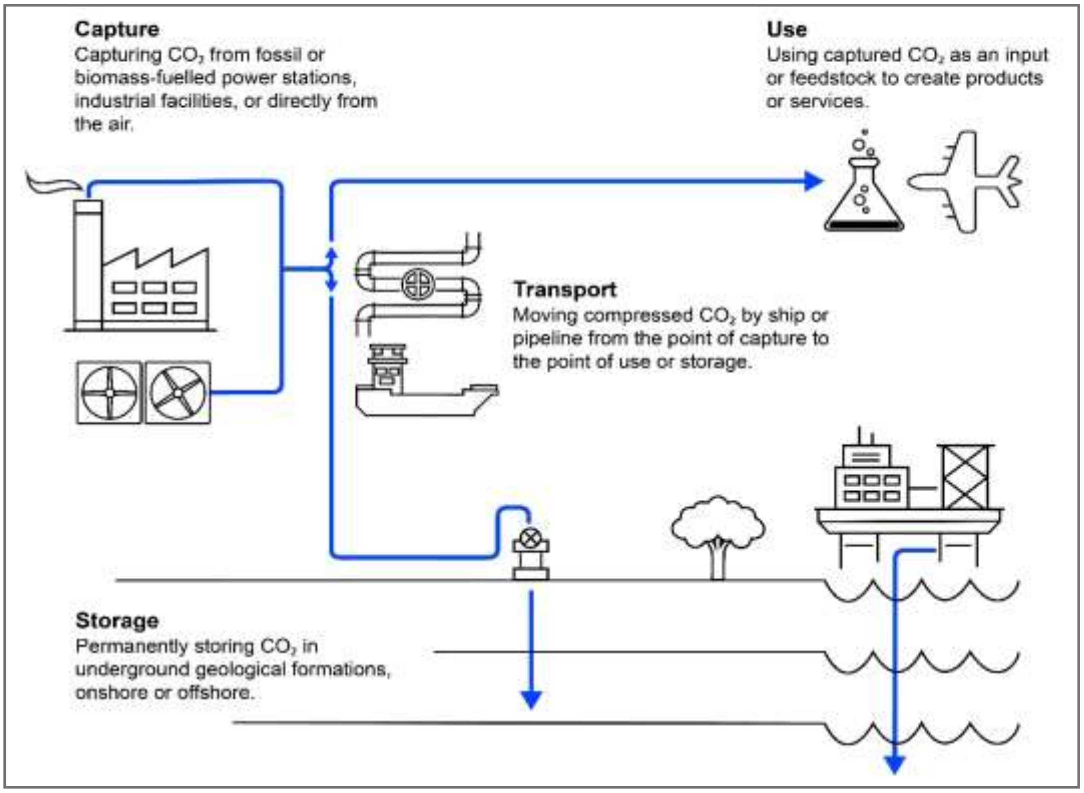


Figure 1. CCUS Process *Source: IEA*

as geothermal, deep saline (brine) water, and uranium.

Carbon storage provides an alternative process for injecting the captured CO_2 into deep geological reservoirs, achieving permanent isolation from the atmosphere. Carbon storage locations may vary and can be categorized as either land or ocean storage.

Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC) are two extensions of traditional CCUS that have been gaining greater attention as pathways to achieve negative net emissions. BECCS employs CCUS techniques to capture and store CO_2 emitted during biomass combustion, while DAC involves direct capture from the atmosphere and either utilization or storage of the captured carbon.

1.2 CCUS Contribution to Decarbonization

In the global fight against climate change, CCUS plays an indispensable role. The Intergovernmental Panel on Climate Change (IPCC), International Energy

Agency (IEA), and International Renewable Energy Agency (IRENA) have predicted the emissions reduction contribution of CCUS in various decarbonization pathways, and in different simulated scenarios, CCUS technology stands out as a key way to achieve temperature control and near-zero emissions targets in this century. However, since each organization has made different assumptions about the decarbonization pathways, there are variations in the predicted results. According to research conducted by IEA, the predicted annual emissions reduction contribution of CCUS is expected to increase from 100 million to 1.67 billion tons between now and 2030, with an average reduction of 490 million tons per year. By 2050, the predicted annual emissions reduction contribution of CCUS ranges from 2.79 billion to 7.6 billion tons, with an average of 4.66 billion tons per year. In terms of the contribution ratio, in the sustainable development scenario published by IEA, the world is expected to achieve net-zero emissions by 2070, with CCUS contributing 9% to emissions reduction in 2050 and 15% to cumulative carbon emissions reduction by 2070. In the deep decarbonization scenario released by the IRENA, CCUS (excluding BECCS) is expected to contribute 6% to annual emissions reduction in 2050, equivalent to about 2.214 billion tons per year.

The IPCC Special Report on 1.5°C further indicates that in order to limit global temperature rise to within 1.5°C and achieve near-zero carbon emissions by 2050, the application of CCUS in various sectors is unavoidable, and a large-scale deployment of negative emission technologies is needed. CCUS technology can also significantly lower the cost of emissions reduction. The IPCC Fifth Assessment Report states that the application of CCUS is an essential component for achieving the lowest-cost climate targets. If CCUS is excluded from the portfolio of emissions reduction technologies, the cost of emissions reduction will increase by 138%.

In light of current technology, the role of CCUS cannot be overstated in the decarbonization efforts of various industries. According to calculations made by IEA, the steel, cement, chemical, fuel conversion, and power generation industries are expected to achieve cumulative emissions reductions of 25%, 61%, 28%, 90%, and 15% respectively between 2020-2070 through the use of CCUS technology in a sustainable development scenario. The variations in the contributions can be attributed to differences in the technical costs of using CCUS in different industries, the feasibility of alternative technologies, and their associated costs. Undoubtedly, CCUS will continue to play a crucial role in reducing global carbon emissions in the future. The IEA's estimates of emissions reductions achieved through CCUS across various industries are illustrated in Figure 2 below.

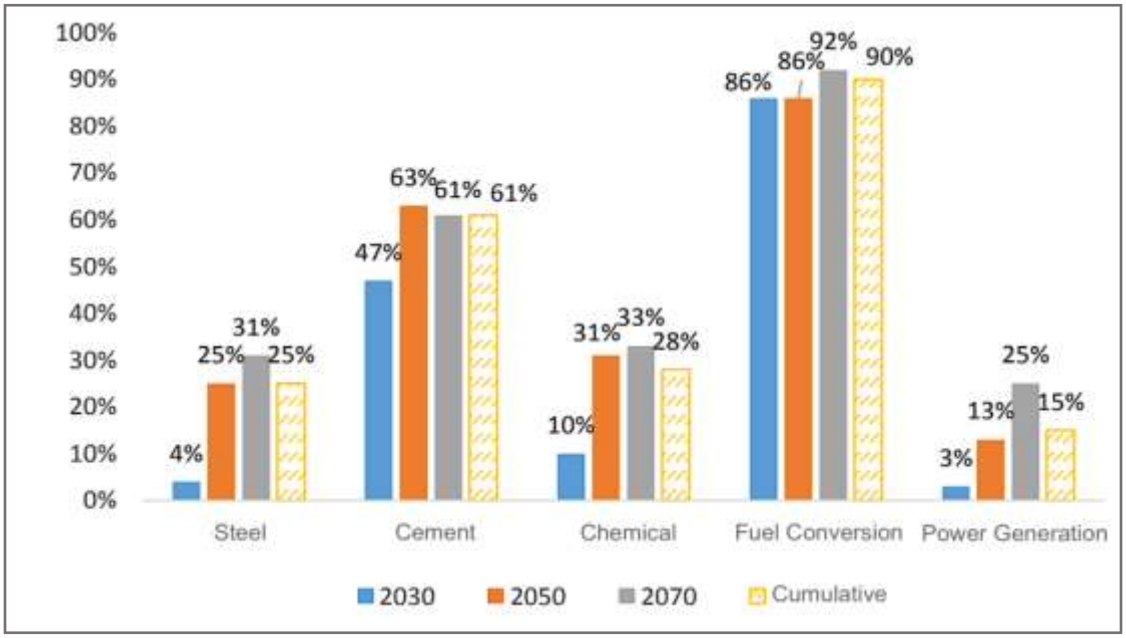


Figure 2. IEA's estimated contributions to emissions reductions through CCUS in various industries

Source: IEA

CCUS Market Potential

2.CCUS Market Potential

On a global level, CCUS technology has entered a new phase of early commercialization development. Firstly, new CCUS business models have emerged, moving away from the development of large independent facilities to the creation of industrial cluster infrastructure with shared CO_2 transport and storage capabilities. This new business model can offer economies of scale and reduce commercial risks. Secondly, the investment environment has improved, with targeted CCUS technology support policies implemented in the United States, the European Union, China, and other regions. The EU's rising carbon price also makes CCUS technology relatively more cost-effective. Finally, countries have announced carbon neutrality targets, making CCUS technology an essential choice for achieving net-zero emissions in the future. In long-term low-emission development strategies submitted to the United Nations Framework Convention on Climate Change (UNFCCC), around 80% of countries acknowledge the role of CCUS technology. The IEA predicts that, in the 2050 zero-carbon scenario, the scale of carbon capture under CCUS technology could reach 7.6 billion tons per year, which is 190 times the global carbon-capture scale of 40 million tons per year in 2020. The

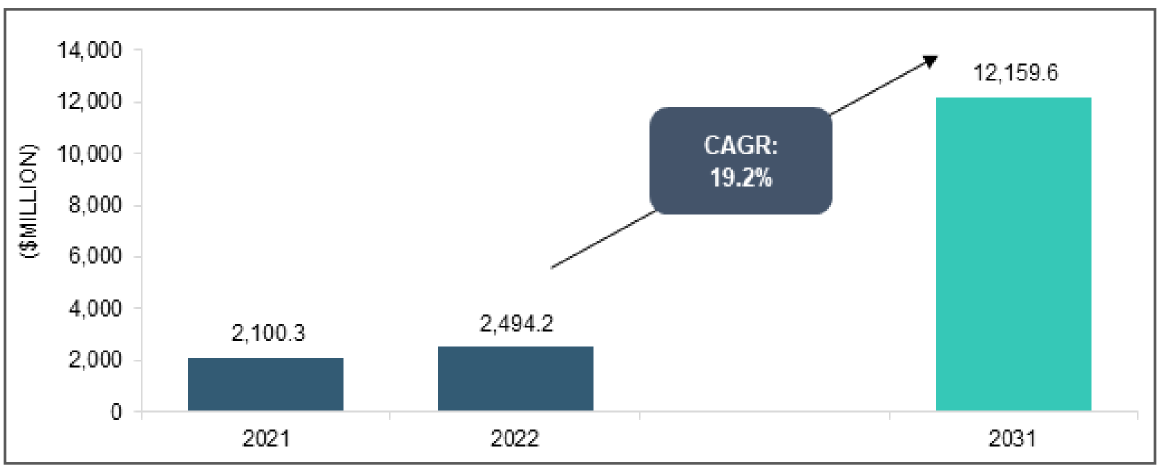


Figure 3. Global CCUS Market Snapshot, $Million, 2021, 2022, and 2031

Source: Carbon Capture Utilization and Storage Market - A Global and Regional Analysis global CCUS market was valued at $2.1 billion in 2021 and is expected to reach $12,159.6 billion in 2031, with a CAGR of 19.2% between 2022 and 2031 (see Figure 3).

According to research by Rystad Energy, the service sector's spending on CCUS development is expected to increase significantly in this decade. In 2022, the total spending for announced commercial projects was $4.4 billion, up from $2.8 billion in 2021. The spending is then anticipated to

the projected total to $52 billion by the middle of the decade (see Figure 4). Based on the already announced projects, it is expected that almost 140 CCUS plants worldwide could be operational by 2025, capturing at least 150 million tons of CO_2 annually if all the projects proceed as planned. Almost two-thirds of the total service spending will go towards equipping the facility with the CO_2 capture component and maintaining operations. The primary driver of spending will be the

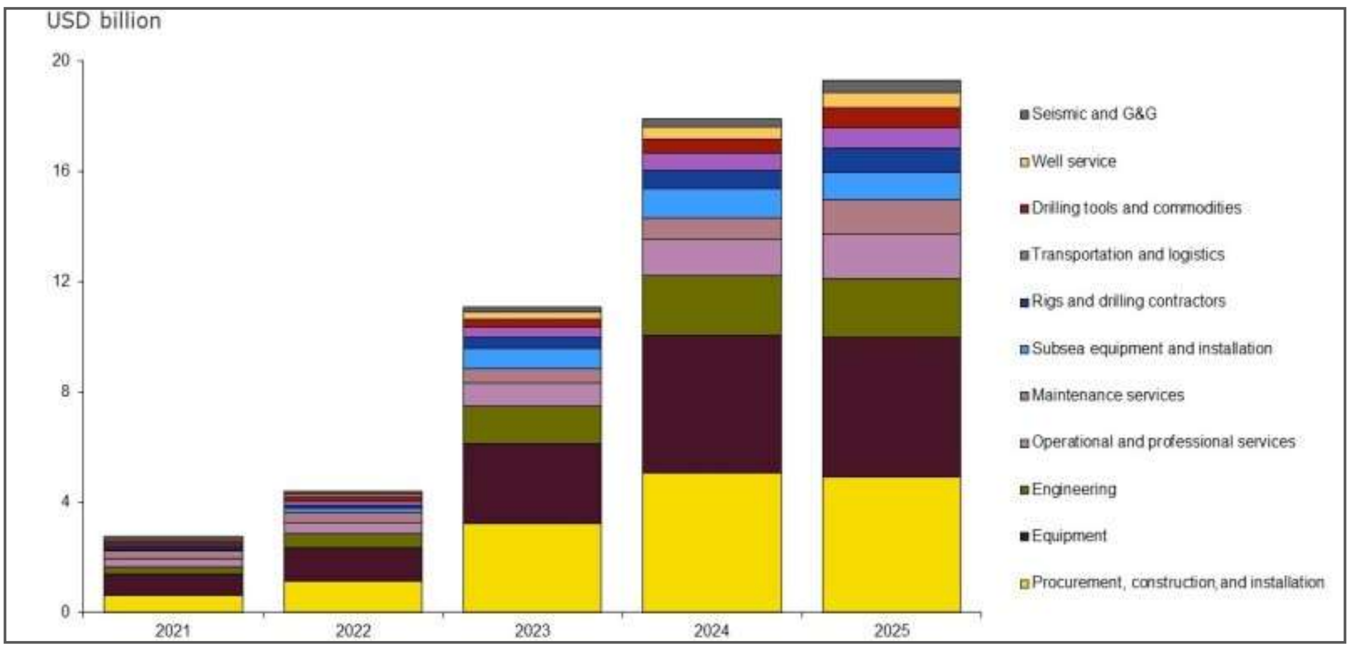


Figure 4. Global CCUS Service Spending by Sectors

Source: Rystad Energy

triple in 2023, reaching $11 billion for the year. Projections indicate that in 2024 and 2025, an additional $18 billion and $19 billion, respectively, will be spent, bringing

engineering, procurement, construction, and installation (EPCI) costs, contributing approximately $35 billion to the total of $55 billion by 2025. Rystad predicts that the annual EPCI spending will reach $12 billion in 2025. Transportation, which follows the capture of CO_2, will require service purchases worth $8.5 billion through 2025. The storage process is expected to incur service purchases of at least $9 billion through 2025, according to Rystad's predictions.

CCUS is viewed as a crucial element for China to attain its climate objectives, given that the country's energy structure is currently dominated by fossil fuels, which will continue to serve as the primary source of energy for the foreseeable future. This reality establishes China as the world's most significant prospective market for the development and deployment of CCUS technology.

China's CCUS market is poised for remarkable growth in the coming years, as projected by IEA, which anticipates that it will become the world's largest by 2040, with an annual capacity of 275 million metric tons of CO_2. In the near term, the energy sector, particularly coal-fired power plants, is predicted to be the primary market for CCUS technology in China. To support this, the Chinese government has set an ambitious target of capturing 1.5 million metric tons of CO_2 per year via CCUS technology by 2025, and 10 million metric tons per year by 2030.

Looking ahead, the prospects for China's CCUS market appear bright, with predictions that it will exceed 330 billion yuan (47.14 billon US dollars) by 2050. According to the "Development Roadmap for Carbon Capture, Utilization, and Storage Technology in China (2019)," a decline in costs, technological advancements, and supportive policies are expected to contribute to the output value of CCUS technology surpassing 20 billion yuan (2.86 billion US dollars) per year by 2025 and more than 330 billion yuan (47.14 billon US dollars) per year by 2050. Even under conservative circumstances, the estimated average annual growth rate from 2025 to 2050 is projected to be an impressive 11.87%. (See Figure 5).

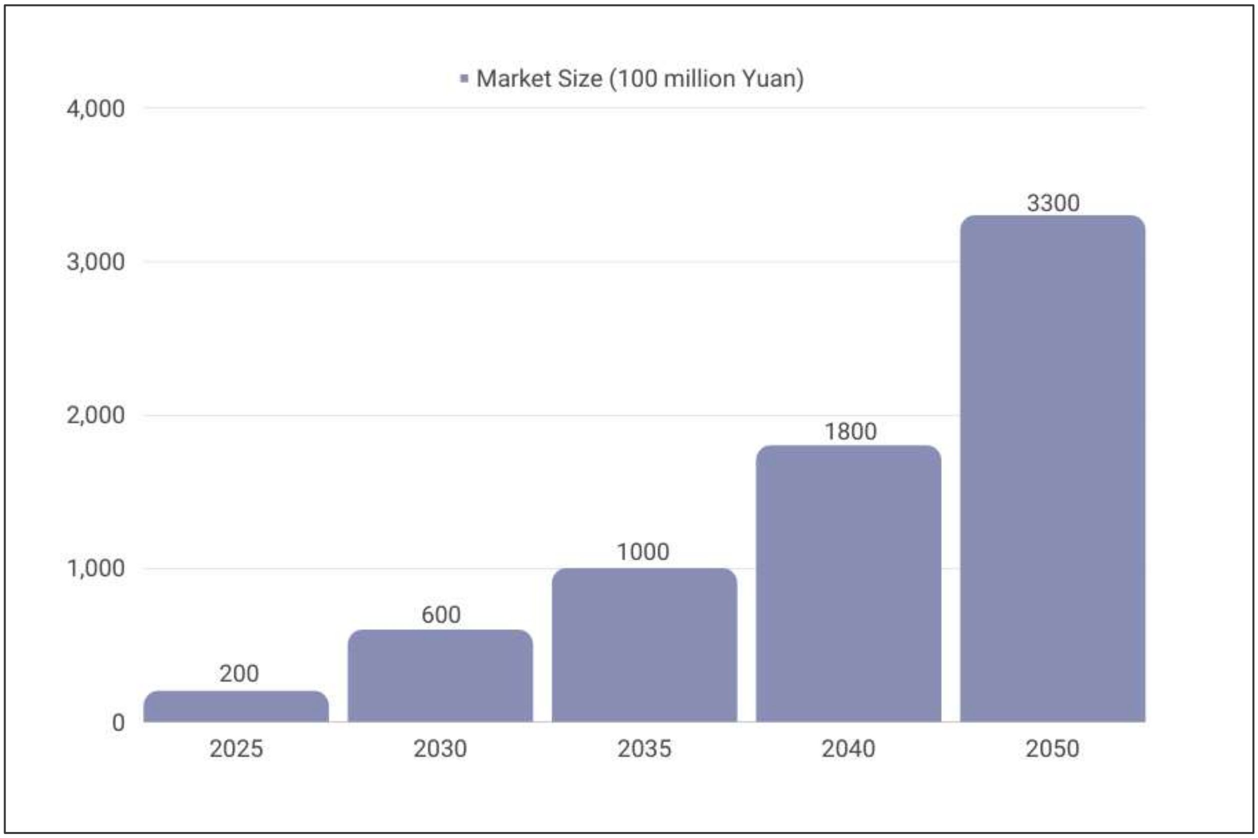


Figure 5. China CCUS Market Size Prediction

Source: Development Roadmap for Carbon Capture, Utilization, and Storage Technology in China (2019)

Government Supports for CCUS

3. Government Supports for CCUS

In recent years, China has taken active steps to address climate change. In 2020, the carbon emissions per unit of GDP decreased by 48.4% compared to 2005. Non-fossil fuels currently comprise 15.9% of the energy mix, and coal consumption has decreased from 72.4% in 2005 to 56.8% in 2020. Furthermore, carbon targets have been integrated into all aspects of national economic and social development policies and are included in local development strategies.

Despite these efforts, fossil fuels still serve as the primary source of energy in China's energy mix. Given that it is a significant manufacturing base, it's likely that fossil fuels will remain the primary energy source for some time. This presents an opportunity for CCUS development and deployment, making China one of the world's largest potential markets for CCUS technology.

3.1 CCUS Importance to China

In 2020, China committed to scaling up its Intended Nationally Determined Contributions in support of sustainable development and the goal of building a shared future for humanity. To achieve this, China pledged to adopt more vigorous policies and measures and to have CO_2 emissions peak before 2030, with the ultimate aim of achieving carbon neutrality before 2060, known as the "dual carbon" targets.

As a developing country, achieving carbon peaking in less than a decade and reaching carbon neutrality within four decades presents a considerable challenge for China, requiring consistent emissions reductions while maintaining a stable economy. To meet these ambitious targets, China has been releasing implementation plans for peaking CO_2 emissions in key areas and sectors, along with a range of supporting measures. The country is also implementing a "1+N" policy framework to ensure success in both carbon peaking and neutrality. Carbon neutrality is achieved when the total amount of greenhouse gases absorbed by natural carbon sinks and Negative Emission Technologies (NETs), such as CCUS technology, is equal to the total amount of carbon emissions caused by socioeconomic activities. CCUS technology is a key component of China's strategy to achieve carbon neutrality. The large-scale application of this technology could significantly reduce carbon emissions from the energy sector and help to achieve deeper decarbonization in industries that are hard to decarbonize, such as steel and cement.

The Chinese government has prioritized the development of CCUS technology in recent years, and the technology has rapidly matured, with numerous demonstration projects in operation. This trend has showcased the emergence of new and more efficient technologies, resulting in a reduction in energy costs over time.

According to the IEA, retrofitting existing power plants and factories with CCUS technology could reduce CO_2 emissions by 600 billion tons over the next 50 years. As China works towards achieving its carbon neutrality goals, the significance of CCUS technology will become more apparent.

3.2 Policy Development

Over 20 years ago, CCUS was introduced to China. So far, China has published around 52 policy documents mentioning CCUS, demonstrating the recognition of its significance. In 2006, the State Council released the "National Mid- and Long-Term Scientific and Technological Development Plan Outline (2006-2020)," in which China first put forth the development of efficient and clean fossil energy technologies, as well as reducing CO_2 emissions to near zero. CCUS technology has been deemed as a crucial technology for targeted support, research, and demonstration.

Subsequently, government agencies such as the State Council and the Ministry of Science and Technology have continued to implement policies to support CCUS, including encouraging its application in areas with hard-to-reduce emissions and high emission density, releasing funds through market mechanisms, exploring sequestered resources, advancing standard development, and researching technology, among others. As of this writing, 299 provincial government institutions have issued CCUS-related development strategies, primarily focused on energy and emission-intensive industries. Table 1 summarizes major policies in support of CCUS in China.

Table 1 List of Major Relevant Policies of CCUS in China

YEAR	ENTITY	NAME	CONTENTS
2006	State Council	National Mid- and Long-Term Development Plan on Science and Technology	For the first time, the development of fossil energy development and utilization technologies with high efficiency, cleanliness and near-zero CO2 emissions was proposed.
2007	MOST, NDRC, Ministry of Foreign Affairs, Ministry of Environment, and others	National Actions on Addressing Climate Science and Technologies	CCUS is listed as one of the key technologies that will be supported and demonstrated with particular emphasis.
2007	Ministry of Science and Technology	National Program on Climate Change	The specific objectives, basic principles, key areas, and policy measures for addressing climate change in China in 2010, and the development of CCUS technology are clearly proposed.
2011	State Council	National Work Plan for Controlling Greenhouse Gas Emissions during the 12th Five-Year Plan Period	Carry out carbon capture pilot projects in thermal power, coal chemical, cement, steel, and other industries, build integrated demonstration projects, and plan in terms of talent building, financial guarantee, and policy support.
	Ministry of Science and Technology	National 12th Five-Year Plan for Science and Technology Development	Strengthen scientific research and technology integration on climate change, comprehensively improve response capabilities, and develop advanced energy technologies including carbon dioxide capture.
2012	State Council	White Paper on China's Energy Policy (2012)	Vigorously promote the clean development of fossil energy, vigorously develop green thermal power, and encourage the construction of pilot demonstration projects for IGCC power generation, CCUS and other technologies.
	MIIT, NRDC, MOST, MOF	National Action Plan for Addressing Climate Change in Industry Sector (2012-2020)	Conduct IGCC projects and CCUS demonstration projects.
	NDRC	The 12th Five-Year Plan for the Development of Coal Industry	Support the research and demonstration of CCUS technology.
2013	State Council	State Council Guidance on Accelerating Energy Saving and Environmental Protection Industry	Strengthen technological innovation, improve the market competitiveness of the energy conservation and environmental protection industry, advance the deployment of CCUS technology and equipment.
	NDRC	Notice on Promoting CCUS Demonstration	Promote CCUS demonstration projects through policies, incentives, strategies, standards and international cooperation.
	Ministry of Ecology and Environment	Notice on Promoting Environmental Protection for CCUS Demonstration Projects	Implement the State Council's "12th Five-Year Plan" to control greenhouse gas emissions and reduce and control all kinds of environmental impacts and risks that may occur in the whole CCUS process.

2014	NDRC	National Plan on Climate Change (2014-2020)	Conduct CCUS all-chain integrated demonstration projects and explore ways of CO2 utilization.
2015	NDRC	Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions	Strengthen the R&D and industrialization demonstration of CCUS and other low-carbon technologies.
2016	MOE	CCUS Environmental Risk Assessment Guidance (Trial)	Clarified risk assessment for CCUS projects.
	State Council	National 13th Five-Year Plan on Science, Technology and Innovation	Focus on CCUS research and development, conduct 1-million-ton per annum post- combustion demonstration projects.
	NDRC	Action Plan for Innovation in Energy Technology Revolution (2016-2030)	Put forward the strategic direction, innovation target and innovation action of CCUS technology innovation.
2019	Ministry of Science and Technology	China Carbon Capture, Utilization and Storage Technology Development Roadmap (2019)	To comprehensively assess the status and potential of CCUS technology development in China, as well as the problems and challenges faced, and propose the development goals of technology R&D demonstration and industrial clusters.
2021	National People's Congress (NRC)	14th Five-Year Plan (2021-2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035	CCUS is included for the first time in the National Five-Year Plan.
	State Council	Action Plan for Carbon Dioxide Peaking Before 2030	China has established a carbon capture, utilization, and storage (CCUS) entrepreneurial technology innovation strategic alliance, along with a special committee and other institutions, to promote technical progress and the application of scientific and technological achievements in the field.
		Responding to Climate Change: China's Policies and Actions	Build full process, integrated and large-scale CCUS demonstration projects, actively participate in international research cooperation and technology exchange, and promote low-cost CCUS technology innovation.
2022	Ministry of Ecology and Environment et al	Action Plan for Achieving Synergies between Carbon and Pollution Reduction	Encourage enterprises in key industries to explore the use of multi-pollutant and greenhouse gas synergistic control technologies and processes, carry out collaborative innovation, and promote the application of CCUS technology in the industrial sector.
	Ministry of Science and Technology	Work Plan for Strengthening the Cultivation System for Talents in Carbon Peaking and Carbon Neutrality	Accelerate the training of CCUS talents and promote the opening of related disciplines in universities to meet the future industrial development needs of the technology, to reserve talents for the future technological development and industrial quality and capacity expansion.

CCUS Demands in Major Sectors

4. CCUS Demands in Major Sectors

CCUS technologies offer several main advantages, including its large emission reduction potential and its ability to reduce carbon emissions from coal power plants, which is particularly suited to China's national conditions.

CCUS has the potential to significantly reduce emissions in various hard-to-abate industries, including the power, energy, and manufacturing sectors. The energy industry, which includes natural gas exploration and hydrogen production, produces large amounts of CO_2 emissions that can be captured and stored using CCUS. Similarly, the manufacturing industry, which encompasses cement, chemical, and steel production, also faces significant emissions reduction challenges, but CCUS technology can help to mitigate these emissions. Overall, CCUS has the potential to play a crucial role in reducing emissions across a range of industries.

4.1 Power Industry

Thermal power generation is a primary contributor of carbon emissions in the power industry. However, the potential for reducing carbon emissions through increased energy efficiency has certain limitations. While replacing thermal power with zero-carbon energy sources can effectively decrease carbon intensity, the unstable output of zero-carbon energy sources such as solar and wind power makes it difficult to replace all thermal power units. China is constructing many nuclear power plants (zero-carbon energy sources), but that will only make up a small percentage of China's future energy mix. As a result, achieving carbon neutrality in the power industry requires the complete elimination of carbon emissions from carbon-emitting energy sources, and CCUS is the only available technical solution. The coupling of negative emission technology with carbon-neutral energy sources provides the technical assurance needed to achieve carbon neutrality in the power industry.

The thermal power industry is currently the main focus of China's CCUS demonstration. It is estimated that by 2025, carbon emissions reductions from applying CCUS in coal-fired power plants will reach 6 million tons per year, and the reduction will continue to grow to peak levels of 200-500 million tons per year by 2040 and maintain this level thereafter. The deployment of

CCUS in gas-fired power will gradually expand as well, reaching a peak in 2035 and then remaining constant. This will lead to a reduction of 20-100 million tons of carbon emissions per year. By installing CCUS in coal-fired power plants, up to 90% of carbon emissions can be captured, making it a relatively low-carbon power generation technology. Approximately 900 million kilowatts of China's current installed capacity will still be in operation by 2050. The deployment of CCUS technology can help to maintain a certain level of coal-fired capacity and delay the premature retirement of some coal-fired assets, thereby reducing resource waste. Retrofitting advanced coal-fired power units with CCUS technology is an important way to unleash the potential for carbon reduction. The applicability standard and cost of the technology are the main factors that affect the retrofitting of existing coal-fired units with CCUS. The applicability standard determines whether a power plant can be considered as a candidate for retrofitting.

4.2 Steel Industry

Recent data indicates that the steel industry is responsible for 7% to 9% of global greenhouse gas (GHG) emissions. As an energy-intensive sector, steel production is the primary consumer of energy and emitter of CO_2 in China, where steel industry CO_2 emissions are second only to those of the power industry and account for approximately 15% of the country's total CO_2 emissions. Although blast furnace ironmaking will remain a significant aspect of steel production activities in the coming decades, CCUS is poised to become one of the critical technologies in reducing worldwide blast furnace carbon emissions. According to IEA's net-zero emission projection, CCUS must account for over 53% of traditional steel production applications by 2050 to achieve net-zero emission goals.

The steel industry in China faces a significant challenge in reducing its carbon emissions. According to estimates, the industry needs to reduce its emissions by 0.02-0.05 billion tons per year by 2030, and by 0.9-1.1 billion tons per year by 2060. Currently, China's steel production process relies heavily on the high-emission blast furnace-basic oxygen furnace method, with electric furnace steel production accounting for just 10% of the total. As a result, about 89% of the energy input in this method comes from coal, leading to higher carbon emissions per ton of steel produced in China. Fortunately, CCUS technology offers a promising solution to reduce emissions in the steel industry. CCUS can be applied to various aspects of steel production, including the production of hydrogen gas in hydrogen-produced ironmaking technology, and the steelmaking process itself. The CO_2 emissions from steel plants in China are mainly of moderate concentration and can be captured through pre- and post-combustion capture technologies. During the steelmaking process, the coke and blast furnace ironmaking stages generate the highest amount of CO_2, and thus, hold the greatest potential for carbon capture. The most commonly used carbon capture technology in China's steel industry involves combusting coke oven and blast furnace gas, followed by capturing the resulting CO_2. In addition to storage and utilization, the captured CO_2 can be directly used in the steelmaking process. These technologies have been successfully tested by Shougang Group and promoted to other steel enterprises.

4.3 Cement Industry

The cement industry is a critical sector in the national economy. Globally, this industry contributes to 7% of the total carbon emissions. Currently, China's cement industry is responsible for roughly 9% of the country's total carbon emissions, making it a significant source of CO_2 emissions in the manufacturing sector. China is the world's top cement producer, accounting for about 60% of global production capacity. According to McKinsey's analysis, to limit the global temperature rise to no more than 1.5℃, China's cement industry must reduce its carbon emissions by over 70% by 2050.

The production of clinkers is the primary source of CO_2 emissions in the cement production process. Clinker is a key component in the production of cement and is a nodular material that forms during the cement kiln stage, where raw materials such as limestone, clay, and other minerals are heated to high temperatures. Emissions from the process of producing lime by burning limestone account for 55-70% of the total carbon emissions, while the high-temperature calcination process requires the burning of fuel, resulting in carbon dioxide emissions accounting for 25-40% of the total carbon emissions. Given the characteristics of the clinker process in cement production, CCUS will be the only choice for the cement industry to achieve carbon neutrality without large-scale replacement of the clinker process with emerging technologies. It is projected to contribute to about 50% of the industry's carbon emissions reduction by 2050. The demand for CCUS to reduce CO_2 emissions in the cement industry is expected to be between 0.1-1.52 billion tons per year by 2030 and 1.9-2.1 billion tons per year by 2060.

4.4 Petrochemical Industry

China's petrochemical industry emits about 1 billion tons of carbon dioxide equivalent, which represents approximately 8% of the country's total greenhouse gas emissions. This sector has a high emission intensity, with some emissions having high concentrations, making it a key area for reducing emissions. Key equipment in the petrochemical industry, such as gasifiers and crackers, require high temperatures, and replacing traditional high-carbon fuels with electric power presents several technical and economic challenges. As a result, CCUS technology is needed to achieve rapid carbon reduction over an extended period of time.

CCUS technology has expanded the channels for CO_2 circulation and utilization in the petrochemical industry. By leveraging CO_2 as a valuable resource, it can be employed as a feedstock for the production of various compounds, including methanol, organic chemicals, and high-polymer polymers. The petrochemical and chemical industries in China have many high-concentration CO_2 emission sources (over 70%), including natural gas processing plants, coal chemical plants, ammonia/fertilizer production plants, ethylene production plants, methanol, ethanol, and dimethyl ether production plants, etc. Compared to low-concentration emission sources, these high-concentration sources have lower capture energy consumption, investment costs, and operation and maintenance costs, providing significant advantages. Thus, high-concentration emission sources in the petrochemical and chemical fields present low-cost opportunities for early CCUS demonstration projects. Early CCUS demonstration projects in China prioritize the combination of high-concentration emission sources and EOR to generate profits through CO_2-EOR. EOR stands for Enhanced Oil Recovery. It is a technique used in the oil and gas industry to increase the extraction of hydrocarbons from oil reservoirs that have already undergone primary and secondary recovery methods. When the market oil price is high, the CO_2-EOR profit can not only offset the cost of CCUS but also create additional economic benefits for CCUS-related stakeholders. This method enables carbon reduction at minimum cost. The demand for CCUS emissions reduction in the petrochemical and chemical industries is expected to be around 50 million tons in 2030, gradually decreasing to zero by 2040.

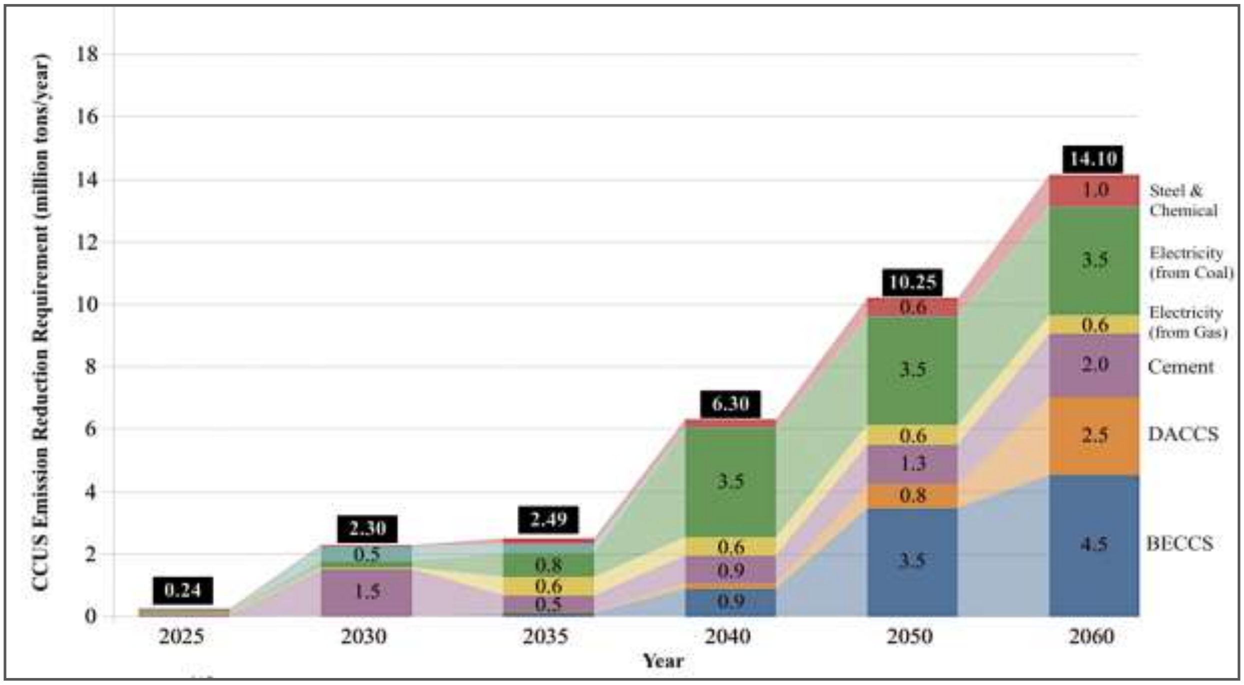


Figure 6. China Estimated CCUS Reduction Requirement

Source: Annual report on carbon dioxide capture, utilization, and storage in China (2021)

CCUS Technology Development

5. CCUS Technology Development

The upstream, midstream, and downstream processes of CCUS technology are interdependent, and together form a CCUS system chain, consisting of four parts: carbon capture, carbon transportation, carbon utilization, and carbon storage. The entire industry chain is interconnected: the upstream end captures CO_2 from emission sources such as fossil fuels, industrial emissions, and biomass utilization, the midstream transports the captured CO_2 to the corresponding location by tank trucks, ships, and other means, and the downstream utilizes or stores the CO_2 to achieve carbon emission reduction. In addition, the Direct Air Capture concept is emerging, and its market potential can be substantial.

5.1 Cabon Capture

Carbon capture is the most crucial step in CCUS technology, accounting for over 70% of the total cost and energy consumption in the entire technology chain. The process mainly involves capturing and separating CO_2 from emission sources and compressing it to a high-purity level. Adequate and high-purity CO_2 collection is essential to ensure the continued implementation of CCUS technology. There are three main methods of carbon capture. The traditional CCUS capture technology primarily captures CO_2 from fossil fuels and industrial processes. The BECCS technology captures CO_2 twice: firstly, by utilizing biomass (which captures CO_2 from the atmosphere), and secondly, by capturing the CO_2 that is released after bioenergy generation, resulting in negative carbon emissions. The third method is direct air carbon capture and storage technology, which directly captures CO_2 from the air and further reduces the concentration of CO_2 in the atmosphere, achieving a negative carbon effect. In the future, carbon sequestration methods will move towards diversification, mainly using traditional capture methods supplemented by bioenergy and direct air capture. According to IEA's research on sustainable development scenarios, it is projected that the proportion of bioenergy and direct air capture within carbon capture technology will increase significantly from 19.6% in 2050 to 36.2% by 2070.

The CO_2 captured by carbon capture technology mainly comes from the use of fossil fuels or carbonates in power generation and industrial processes, as well as the escape of CO_2 during some energy extraction processes. The major carbon sources in China are mainly from industries such as thermal power plants, cement, steel, and coal chemical processes. Due to the different concentrations and impurity components of carbon sources in different industries, the capture technology used is different. Currently, capturing from high-concentration emission sources faces fewer technical challenges and is more mature. In addition, in terms of the single enterprise emission scale, the carbon emission scale of thermal power plants, cement, steel, and coal chemical industries are relatively large. Enterprises in these industries are mainly concentrated in the economically developed eastern regions, similar to the distribution of China's population and economic development.

Carbon capture involves two main processes: capture and separation, which are further divided into various technical routes.

The capture process can be classified into three technical routes based on the order of carbon capture and combustion: pre-combustion capture, oxy-fuel capture, and post-combustion capture. Among these, post-combustion capture is currently the most widely used and mature technology with higher applicability and capture rate. The gap between domestic and foreign technologies is relatively small, making it the most advantageous technology. Pre-combustion capture and oxy-fuel combustion capture technologies have greater limitations in application scenarios, and their related demonstration projects account for a relatively small proportion. However, their development needs to be emphasized for diversification of technological development routes. The concentration and flow rate of CO2 emissions are significant factors that impact the cost of carbon capture. The capture cost has an inverse correlation with the concentration of CO2 emissions. Post-combustion capture has more gas impurities and higher energy consumption, leading to higher investment and operating costs. Therefore, the development of pre-combustion capture and oxy-fuel combustion capture technologies is still essential to optimize the cost of carbon capture.

In the separation process, carbon capture separation technologies include chemical absorption, physical absorption, and membrane separation. Chemical absorption technology, which has a large absorption capacity and high efficiency, includes organic amine method, ammonia absorption method, hot potassium carbonate method, and ionic liquid absorption method. Organic amine method is currently the main chemical absorption method and has been widely used in domestic carbon capture demonstration projects. However, all three separation methods have their strengths and need to be developed and applied in their respective advantageous sectors to achieve the optimization of CO_2 absorption and separation effect.

The current mainstream international carbon capture technology is the first-generation post-combustion capture combined with chemical absorption, which has now entered the stage of large-scale demonstration and application. In China, the pre-combustion physical absorption method has already reached the commercial application stage, while the post-combustion chemical absorption method is still in the pilot stage. Most other capture technologies are currently in the stage of industrial demonstration. Second and third-generation technologies, such as new membrane separation technology, new absorption technology, new adsorption technology, pressurized oxygen-enriched combustion technology, and chemical looping combustion technology, are all in the research and development stage. It is anticipated that after these technologies mature, energy consumption and costs will be reduced by over 30% compared to the first-generation technologies.

5.2 Carbon Transportation

CO_2 transportation is an intermediate link in the CCUS technology system. Possible transportation methods include pipeline transportation and various modes of transportation, such as tank truck and ship transportation, which are suitable for different scenarios. For example, pipeline transportation is suitable for large-scale and long-distance transportation of CO_2; highway tank trucks are suitable for small-capacity and short-distance transportation, railway tank trucks are suitable for large-capacity and long-distance transportation; shipping has a large transportation capacity and is suitable for transporting CO_2 for offshore carbon storage. Considering the advantages and disadvantages of different transportation methods, the CCUS transportation strategy should be determined by comprehensively considering the capacity, distance, cost, market factors, and traffic layout along the line.

From a technological development and practical project standpoint, tank truck and ship transportation technologies in China have reached the commercial application stage. However, the scale of China's existing CCUS demonstration projects is relatively small, with over 70% of them relying on tank truck transport, and only some of the CO2 from Sinopec East China Oil and Gas Field and Lishui 36-1 Gas Field being transported by ship. Land pipeline transportation technology is the most promising and economically scalable technology. CO_2 pipeline transportation technology has been used for over 30 years in North America, where a pipeline network of over 8,000 km has been built, accounting for about 85% of the global total length and primarily used for enhanced oil recovery. However, pipeline transportation technology is still in the experimental stage in China, with only 70 km of pipelines built to date. Three CCUS projects in China have used land pipeline transportation technology, all of which are low-pressure CO_2 transport projects drawing on experience from oil and gas pipeline transportation. These projects have a transport capacity exceeding 1 million tons per year, such as the CNPC Jilin Oilfield CCUS project, which has a transport distance of up to 20 km. While China has the ability to design large-scale pipelines and is developing relevant design specifications, technology for transporting CO_2 through underwater pipelines lacks experience and is still in the research stage domestically.

5.3 Carbon Utilization

Carbon utilization refers to the process of utilizing captured CO_2 as a valuable resource through various engineering and technological means. The physical, chemical, or biological properties of CO_2 can be utilized to increase energy production and efficiency, extract mineral resources, chemical synthesis, agricultural production, and more. By enhancing the economic value of carbon and achieving carbon element circulation, carbon utilization contributes to reducing carbon emissions.

Carbon utilization can be divided into geological utilization, physical utilization, chemical utilization, biological utilization, and mineralization utilization. According to the application method, it can be divided into direct utilization and conversion utilization of CO_2. The development of carbon utilization technology in China has shown promising results in the context of energy conservation and emissions reduction. For CCUS application in China, carbon utilization is the primary method, accounting for over 70% of all CCUS projects' total captured carbon emissions.

However, carbon utilization is a challenging component in CCUS and needs a great deal of innovations to improve its efficacy. While CO_2 is widely available, activating its chemical properties and finding suitable catalysts for the complex reaction paths and low product selectivity remain a significant challenge. Countries are focused on breaking through high-temperature and high-pressure environmental bottlenecks and finding suitable catalysts as the key breakthroughs for carbon utilization technology.

Among the various technology types, geological utilization has achieved a certain scale and has become the primary carbon utilization method in China. Geological utilization injects captured CO_2 underground to enhance the extraction of energy and resources under geological conditions. In China, geological utilization accounts for 48% of carbon utilization, sequestering over 5.8 million tons of CO_2.

Additionally, chemical utilization and biological utilization are making steady progress. In the field of chemical utilization, new technologies such as electrocatalysis and photocatalysis are rapidly emerging. For example, the technology to synthesize organic carbonates, degradable polymers, and polyester materials using CO_2 is promoting the accelerated circulation of carbon elements. In terms of biological utilization, significant breakthroughs have been achieved in microalgae fixation and gas fertilizer utilization technologies.

Carbon utilization technology is still in its early stages, and further development is crucial to achieve carbon circulation and improve the economic benefits of this technology. CO_2 utilization is a key task listed in China's "Energy Technology Revolution and Innovation Action Plan (2016-2030)." The further development of biological and chemical utilization technologies will expand the scope of commercial applications for carbon utilization beyond geological utilization.

5.4 Carbon Storage

Carbon storage technology can effectively achieve "carbon sequestration" and establish a "reserve pool" of carbon elements by treating a portion of the CO_2 and injecting it into the subsurface or seabed at a certain depth in a liquid or liquid-gas mixture state, which isolates it from the atmosphere.

Carbon storage technology is mainly divided into three categories: onshore saline formation storage, offshore saline formation storage, and depleted oil and gas field storage. Among them, onshore saline formation storage dominates and is one of the most important carbon storage locations. Firstly, from the perspective of storage conditions, onshore saline formations have excellent geological conditions, good closure, and wide distribution, making them the most ideal location for CO_2 storage. Depleted oil and gas field storage requires complete structures, closed and stable geological environments, and detailed geological exploration foundations, which have more limiting conditions. Secondly, from the perspective of storage potential, China's onshore saline formation geological storage potential is large, at about 1.21-4.13 trillion tons. According to the suitability evaluation map of CO_2 geological storage in China's major sedimentary basins and adjacent sea areas by the Water Resources and Environment Institute, the deep saline formations in China have a storage potential of more than 90% of the total potential, making it the main storage space for achieving large-scale CO_2 geological storage in China's future. Among them, the three largest onshore storage areas in the Songliao Basin, Tarim Basin, and Bohai Bay Basin can store half of the total amount of CO_2 stored.

From a technological development perspective, China's onshore saline formations have completed project demonstrations and made relatively rapid progress. China's onshore saline formation storage technology has completed a 100,000 t/year demonstration, which is the National Energy Group's Erdos 100,000 ton/year CO_2 saline formation storage project. This project achieved its target of injecting 300,000 tons of CO_2 and stopped injection in 2015. Another project of the National Energy Group, the Guohua Jinjie power plant's 150,000 ton/year CCUS demonstration project after combustion, plans to store captured CO_2 in saline formations and is currently under construction. Other carbon storage technologies have completed pilot scheme design and verification. Additionally, in 2021, China National Offshore Oil Corporation announced the official launch of China's first offshore CO_2 storage demonstration project in the Enping 15-1 oilfield cluster. More commercial applications of carbon storage methods are expected to be realized in the future.

5.5 Direct Air Capture

As mentioned earlier, the Direct Air Capture (DAC), also referred to as Direct Carbon Removal (DCR) or Carbon Dioxide Removal (CDR), is an advanced technological solution aimed at combating climate change by effectively lowering the levels of greenhouse gases in the atmosphere. DAC provides a range of benefits, including its flexibility, ability to swiftly respond to historical emissions, effective climate risk management, support for sectors that are challenging to decarbonize, and the potential for climate restoration. However, it is important to note that DAC should be complemented by efforts to reduce emissions in order to adopt a comprehensive approach to tackling climate change.

The United States and Europe prioritize the development of DAC technology. In recent years, they have made significant investments in technical research and engineering demonstrations. Multiple ongoing projects have set a goal of reaching a commercial scale of one million tons per year. There remains a notable disparity between China's DAC technology development and that of the United States and Europe. It is crucial for China to conduct further research, accelerate development efforts, and deploy industrial demonstrations in order to bridge this gap and promote the synchronized advancement of DAC technology and standards. Presently, the China Huaneng Clean Energy Research Institute is actively engaged in the development and industrial demonstration project of DAC technology in China. The completion of China's first set of DCR industrial demonstration equipment is anticipated by 2024.

CCUS Projects in China

6. CCUS Projects in China

Currently, China has more than 40 CCUS demonstration projects either in operation or under construction. These projects have a combined carbon capture capacity of 3 million tons per year and are located across 19 provinces. The projects utilize a range of CCUS methods, including pure capture initiatives for power and cement plants, and varied storage and utilization projects such as CO_2-EOR, CO_2-ECBM, in-situ leaching of uranium, syngas preparation from gasification, microalgae fixation, and saline formation storage. Most of these projects are small-scale capture-enhanced oil recovery (EOR) demonstrations in the petroleum, coal chemical, and power industries. Large-scale industrial demonstrations that use various combinations of technologies throughout the entire process are still in the planning stage. Notably, the EOR project of the Jilin Oilfield of China National Petroleum Corporation is the largest EOR project in Asia, with over 2 million tons of CO_2 injected to date. Additionally, the Guohua Jinjie power plant of State Energy Group's 150,000-ton-per-year full-cycle demonstration project for combustion CCS is the largest CCUS demonstration project for coal-fired power plants in China. The Table 2 below provides a summary of the CCUS project landscape in China.

Table 2. Major CCUS Projects in China

Project Name	Location	Capture					Transport	Storage		Year Start
		Industry Type	Business Entity	Source	Technology	Scale 10k-tons/yr	Means of Transport	Storage site	Storage Technology	
National Energy Group Ordos Saline Aquifer Storage Project	Ordos, Inner Mongolia	Coal to Oil	National Energy Investment Group Co., Ltd. Ordos, Coal-to-Oil Branch Company		Pre-combustion (physical adsorption)	10	Tank truck	Ordos Basin	Saline storage	2011
Yanchang Petroleum Shaanbei Coal Chemical Co., Ltd. 50,000 tons/year CO2 capture and demonstration	Xi'An, Shan Xi	Coal to Gas	Shan Xi Yanchang Petroleum Yulin Coal and Chemical Co., Ltd. gasification plant		Pre-combustion (physical adsorption)	30	Tank truck	Shaan'Xi Yulin Jingbian Oilfield	EOR	2013
China National Nuclear Corporation Tuliemiao in-situ uranium mining	Tongliao, Inner Mongolia						Tank truck	Qianjiadian Uranium Deposit	In-situ leaching uranium mining	N/A
CNPC Jilin Oilfield CO2-EOR research and demonstration	Songyuan, Jilin	Natural Gas Processing	Changling natural gas processing plant of Jilin Oilfield		Pre-combustion (associated gas separation)	60	Pipeline	Daqingzijing Oilfield	EOR	2008
Huaneng Gaobeidian Power Plant	Beijing	Coal-Burning Power Plant	Huaneng Gaobeidian Power Plant		Post-Combustion (chemical absorption)	0.3				2008
Huaneng Green Coal-fired Power Generation IGCC Capture, utilization and storage in power plant	Tianjin	Coal-Burning Power Plant	Tianjin Binhai New Area 400 MW coal gasification combined cycle demonstration unit		Pre-Combustion (chemical absorption)	10	Tank truck		Release	2015
Huaneng Green Coal-fired Power Generation IGCC, Capture, utilization and storage in power plant	Tianjin	Coal-Burning Power Plant	Tianjin Binhai New Area 400 MW coal gasification combined cycle demonstration unit		Pre-Combustion (chemical adsorption)	2	Tank truck	Marketed and sold off commercially	Food application	2012

Lianyungang Clean Energy Power System Research Facility	Lian Yun Gang, JiangSu	Coal-Burning Power Plant	Lianyungang Clean Energy Innovation Industrial Park	400 MW IGCC unit	Pre-Combustion	3	Pipeline		Release	2011
Huaneng Shidongkou Power Station	Shidongkou, Shanghai	Coal-Burning Power Plant	Huaneng Shanghai Shidongkou Second Power Plant	600 MWe ultra-supercritical unit	Post-Combustion (chemical absorption)	12		Marketed and sold off commercially	Industry and food application	2009
Sinopec Shengli Oilfield CO2-EOR Project	Dongying, Shandong	Coal-Burning Power Plant	Shengli Power Plant		Post-Combustion (chemical absorption)	4	Tank truck	Dongying Shengli Oil Field, Number G89	EOR	2010
Sinopec Central Plains Oilfield CO2-EOR Project	Puyang, Henan	Fertilizer Plant		Synthetic Ammonia Tail Gas from Fertilizer Plant	Pre-Combustion (chemical absorption)	10	Tank truck	Central Plains Oil Field	EOR	2015
China Power Investment Corporation Chongqing Shuanghuai Power Plant Carbon Capture Demonstration Project	Chongqing	Coal-Burning Power Plant	Chongqing Hechuan Shuanghuai Power Plant	2 sets of 300MW units	Post-Combustion (chemical adsorption)	1		Self-use	Welding protection, hydrogen cooling replacement of generators in power plants, etc.	2010
China United Coal Flooding CBM Project (Shizhuang)	Qinshui, Shanxi	Purchased gas					Tank truck	Qinshui Basin Shizhuang Block	ECBM	2004
MW Oxyfuel Demonstration	Wuhan, Hubei	Coal-Burning Power Plant	Hubei Jiuda (Yingcheng) Company	Second thermoelectric workshop	Oxyfuel Combustion	10	Tank truck	Marketed and sold off commercially	Industrial application	2014
China United Coal Flooding CBM Project (Liulin)	Liulin, Shanxi						Tank truck	Ordos Basin, Liulin Block	ECBM	2012
Karamay Dunhua Petroleum-Xinjiang Oilfield CO2-EOR Project	Karamay, Xinjiang	Methanol Plant	Xinjiang Dunhua Petroleum Technology Co., Ltd.	PetroChina Karamay Petrochemical Company Methanol Plant	Pre-combustion (chemical absorption)	10	Tank truck	Junggar Basin Xinjiang Oil Field	EOR	2015

Changqing Oilfield CO_2-EOR Project	Xi'an, Shaanxi	Methanol plant	Ningxia Deda Gas Development Technology Co., Ltd.	Shenning Coal Chemical Methanol Plant	Pre-Combustion	5	Tank truck	Jiyuan Oilfield, Changqing Oilfield, Dingbian County, Shaanxi Province	EOR	2017
Daqing Oilfield CO_2-EOR Demonstration Project	Daqing, Heilongjiang	Natural gas processing	Daqing Tianranqi Branch Xushenjiu Natural Gas Purification Plant	Xushen Gas Field	Pre-combustion (associated gas separation)		Tank truck (commercial sales) + pipelines (Xushenjiu Natural Gas Purification Industry)	Block Shu 101 outside Changyuan, Block Bei 14 in Hailaer Oilfield	EOR	2003
Conch Group Wuhu Baimashan Cement Plant 50,000 tons of CO_2, Carbon capture and purification demonstration project	Wuhu, Anhui	Cement factory	Wuhu Baimashan Cement Plant		Pre-combustion (chemical absorption)	5	Tank truck	Marketed and sold off commercially		2018
China Resources Power Haifeng Carbon Capture Test Platform	Haifeng, Guangdong	Coal-Burning Power Plant	Sino-British (Guangdong) CCUS Center	Unit 1 of China Resources Haifeng Power Plant	Post-combustion	2				2019
Sinopec East China Oil and Gas Field CCUS Full Process Demonstration Project	Dongtai, Jiangsu	Chemical Plant	Jiangsu Huayang Liquid Carbon Co., Ltd. Taixing Carbon Dioxide Plant	Sinopec Nanjing Chemical Company	Pre-Combustion	10	Tank truck, tank boat	East China Oil and Gas Field Zhenwu, Huazhuang, Shuaiduo, Caoshe and Haian blocks	EOR	2005
Sinopec Qilu Petrochemical CCS Project	Zibo, Shandong	Chemical Plant	China Petrochemical Corporation		Pre-Combustion	35	Pipeline		EOR	2017
Xinjiang Zhundong CO_2-EWR Field Pilot Test	Changji Hui Autonomous Prefecture, Xinjiang Uygur Autonomous Region				Post-Combustion		Tank truck		Experiment	2018

National Energy Group Guohua Jinjie Power Plant 150,000 tons/year post-combustion CO2 capture and storage full-process demonstration project	Yulin, Shaanxi	Coal-Burning Power Plant	National Energy Investment Group Co., Ltd.		Post-Combustion	15			Saline storage	2020
Huaneng natural gas power generation flue gas post-combustion captures experimental device	Beijing	Gas Power Plant	China Huaneng Group Co., Ltd.		Post-Combustion	0.1				2012
Huaneng Changchun Thermal Power Plant Post Combustion Capture Project	Changchun, Jilin	Coal-Burning Power Plant	China Huaneng Group Co., Ltd.		Post-Combustion	0.1				2014
Beijing Liulihe Cement Kiln Tail Flue Gas Carbon Capture and Application Project	Beijing	Liulihe Cement Plant	Beijing Liulihe Cement Co., Ltd.		Pre-Combustion	0.1			Industry Applications	2017
Lishui 36-1 gas field CO2 separation, liquefaction and dry ice production project	Wenzhou, Zhejiang	natural gas extraction	China National Offshore Oil Corporation		Pre-Combustion	5	Sea transport / tank truck		Commercial Application	2019
300Nm3/h flue gas CO2 chemical absorption pilot test platform	Hangzhou, Zhejiang	Oil Fired Boiler			Post-Combustion	0.05			Experiment	2017
Qilu Petrochemical - Shengli Oilfield CCUS Project	Zibo, Shandong	Chemical Plant	Shengli Oil Field	Fertilizer plant tail gas	Low temperature methanol wash	100	Tank truck	Dongying, Zibo	Oil Storage	2022
Huaneng Coal Power CCUS Project	Zhengning, Gansu	Coal-Burning Power Plant	China Huaneng Group Co., Ltd.			150				2023
Daqing Oilfields demonstration project	Daqing, Heilongjiang		China National Petroleum Corporation			140				2025
Jilin Oilfield Demonstration project	Jilin, Dongbei		China National Petroleum Corporation			100				2025
Ningxia 3 million-ton CCUS demonstration project	Ningdong Energy and Chemical Industry Base	Coal chemical industry	National Energy Group Ningxia Coal Industry Ltd.,	Coal-to-Oil plants emissions	Post-Combustion	300			CO_2-EOR	2023-2025

			PetroChina Changqing Oilfield Branch							

Other projects include:

Shaanxi Yanchang Petroleum plans to build a 5-Mt scale CCUS project and will complete a 1 Mt-scale CCUS industrial demonstration by the end of the 14^{th} Five-Year Plan.

Guangdong Development and Reform Commission, CNOOC, Shell and ExxonMobil signed an MoU to jointly study a 10-Mt-scale CCUS cluster in the Daya Bay area in June 2022.

In November 2022, Sinopec, Shell, Baowu Steel and BASF announced that they will conduct a collaborative study to launch an open-source 10-Mt-scale CCUS project in East China.

U.S.-China Collaboration on CCUS

7. U.S.-China Collaboration on CCUS

The United States and China have a robust history of working together to address the climate crisis, with a particular emphasis on CCUS as a key area of cooperation. This focus on CCUS has been consistent across policy development, multilateral meetings, and bilateral agreements.

The United States views China as a potentially profitable and large-scale market for CCUS utilization and applications. The two countries first began collaborating on CCUS in 2005 when China launched its own program to explore the potential of this technology. During the Obama Administration (2008-2016), the United States and China established eight agreements aimed at jointly reducing greenhouse gas emissions, with half of these agreements centered on CCUS.

Despite a decrease in overall governmental cooperation during the Trump Administration (2016-2020), scientific and regional collaboration on joint CCUS efforts remained prominent. Most recently, the use of CCUS was highlighted as a strategic priority in the U.S.-China Joint Glasgow Declaration on Enhancing Climate Action, which was signed in November 2021.

7.1 CCUS in the United States

The development of CCUS technology is a critical component of the United States' efforts to reduce greenhouse gas emissions and address climate change. As a global leader in CCUS technology development, the United Sates has made significant investments in research and development in this field. The Terrell Natural Gas Plant in Texas, built in 1972, is the oldest CCUS project in the world, and it continues to capture and permanently store CO_2 at a rate of 0.4 Mtpa, while also using it for enhanced oil recovery. The Shute Creek natural gas processing plant, owned by ExxonMobil and located in Wyoming, is currently the largest CCUS project in the world, with the capacity to capture 7 million tons of CO_2 per year.

The U.S. Department of Energy (DOE) has established the National Carbon Capture Center (NCCC) to fast-track the progress of CCUS technology. The NCCC provides researchers and industry partners with access to top-notch testing facilities and resources to support their efforts. The DOE has been funding research into innovative CCUS technologies such as advanced solvent-based capture, post-combustion capture, and oxy-fuel combustion. The

U.S. government has also been providing support for pilot projects to prove the viability of these technologies at a commercial scale. In addition to funding, the U.S. government has put in place a comprehensive regulatory framework to support the growth of CCUS technology. This framework includes tax incentives and funding programs to encourage investment in this field. In the Biden Administration's Inflation Reduction Act (IRA), one of the most crucial legislative tools demonstrating its commitment to combating the global climate crisis, the 45Q tax credit was extended and expanded to stimulate the growth of CCUS projects. The 2022 changes to 45Q substantially increase the availability of federal income tax credits for domestic CCUS projects, make it easier for joint CCUS projects to qualify for 45Q credits, and provide significant incentives due to the sizable revenue increase. As projects constructed prior to January 2033 qualify for this tax credit, there is an expected boom in the number of projects in the upcoming years. The U.S. Environmental Protection Agency (EPA) has also established strict rules and guidelines for the management of captured CO_2, ensuring that it is stored and used safely and securely. With these measures in place, the U.S. continues to lead the way in the development of CCUS technology, making it a critical tool in the fight against climate change.

Private sector companies in the United States, particularly major oil and gas corporations like ExxonMobil, Shell, and Chevron, have invested significantly in the research and development of CCUS technologies. The U.S. oil and gas industry presents ample opportunities for the practical implementation of CCUS technologies, particularly in the areas of EOR and natural gas processing. Additionally, there are already several large-scale CCUS projects underway in the U.S., such as the Petra Nova project in Texas.

Millions of dollars in R&D funding have also been contributed from the personal funds of tech industry executives. For instance, in 2021, Elon Musk announced a $100 million prize for promising CCUS technologies. In 2022, the Chan Zuckerberg Initiative donated $21 million to UCLA Engineering's Institute for Carbon Management to test three promising carbon removal solutions, including an electrochemical DAC process.

Furthermore, there has been a recent surge in U.S. venture capital investment in startups focused on CCUS. For example, In 2022, Pasadena-based CarbonCapture secured USD$35m in Series A funding to develop DAC technology using zeolites. Massachusetts-based start-up Verdox is developing a technology which uses only electricity to capture and release CO_2, potentially reducing energy consumption by 70 percent. Investors, including Bill Gates-led Breakthrough Energy Ventures, have committed USD$80m to the project. This growing trend of investment in CCUS startups highlights the increasing importance of this technology in combating climate change, as well as its potential for high returns on investment. With the U.S. government setting aggressive targets for reducing emissions and increasing investment in clean energy, the demand for CCUS technology will rise, creating ample opportunities for further U.S. development in this field.

The United States has taken a proactive approach in participating in international collaborations and partnerships aimed at advancing the development of CCUS technologies. This has resulted in its active involvement in organizations such as the Carbon Sequestration Leadership Forum and the Global CCS Institute. The US has also formed strategic partnerships with countries such as Australia, Canada, and the European Union to jointly invest in and advance CCUS technology. This collaboration has established the US as a leading player in the field of CCUS and it continues to work closely with other nations to promote the widespread adoption of this critical technology globally.

7.2 U.S.-China Collaboration Opportunities

Thanks to its domestic energy policies, the United States had a significant early advantage in the development of CCUS technology. Overall, the United States developed and matured the technology much earlier than China, with research and development in the CCUS field starting 10 to 20 years earlier.

2020 was a pivotal year for the development of CCUS in China. Prior to this, CCUS technology in China was mostly in the experimental and demonstration stages. In September 2020, China proposed the "2030 peak carbon emissions and 2060 carbon neutrality" strategy, marking a new stage in the development of CCUS in China. Since 2021, the research and demonstration applications of China's CCUS projects have advanced to a new stage, with the commercial utilization of pre-combustion physical absorption in the carbon capture process and uranium mine in-situ leaching technology in the carbon utilization process. Despite impressive achievements, China's CCUS development still lags its ambitious carbon neutrality goals. China still has a shortage of CCUS-related facilities and large-scale projects, with some key technologies lagging international advanced levels. According to data from SAI Consulting, in 2021, 88.9%

of CCUS projects in China had a capture scale of less than 300,000 tons/year, while projects with a capture scale exceeding 600,000 tons/year accounted for only 3.7%, while the average annual carbon capture scale of a single CCUS project in the United States was about 2.4 million tons.

In the field of CCUS, China maintains an open attitude and actively engages in cooperation with foreign governments and international organizations. Its partners include the United States, the United Kingdom, the European Union, Australia, Norway, Japan, and others. For instance, China is a member of the Carbon Sequestration Leadership Forum (CSLF), led by the United States, and a member of the Global CCS Institute (GCCSI), established by the Australian government. China also participates in multiple CCUS cooperation projects under the Asia-Pacific Economic Cooperation (APEC).

International cooperation has become a crucial component of China's CCUS development strategy. The United States is at the forefront of CCUS technology, with its advanced and extensive industrial system fostering a robust CCUS industry and cutting-edge technological prowess. The United States has incubated and nurtured various enterprises along the CCUS supply chain that excel in various stages, making them top-tier technology companies in the field. Beyond these globally renowned energy corporations, numerous consulting service companies that focus on the development of specific CCUS technologies are also worth noting. The existence of diverse market subjects is a cornerstone of the thriving CCUS industry in the United States. The thriving industrialization and commercialization of CCUS in the United States present significant business opportunities for both China and the United States. Considering the extensive history of CCUS cooperation between China and the United States and China's rapidly expanding carbon neutrality market, more opportunities for commercial cooperation in CCUS between the two countries are expected in the future.

The Table 3 presented below outlines the major CCUS technologies and solutions currently available in the Chinese market and their corresponding development stages. Notably, certain technologies such as post-combustion chemical absorption, post-combustion membrane separation, pipeline transportation, enhanced oil recovery, enhanced natural gas recovery, hydrate substitution, and enhanced deep saline aquifer recovery and storage significantly lag foreign technologies. Therefore, it is advisable to prioritize collaboration in these areas. Additionally, numerous opportunities for cooperation exist along the supply chains of CCUS technologies, especially in manufacturing, equipment, and technology consulting services.

Table 3. List of Major CCUS Technologies / Solutions in China		
CCUS Process	**CCUS Technologies / Solutions**	**Status in China**
Carbon Capture	Pre-combustion: physical absorption method	Commercial application
	Pre-combustion: chemical adsorption method	Industrial demonstration
	Pre-combustion: pressure swing adsorption method	Industrial demonstration
	Pre-combustion: low-temperature distillation method	Industrial demonstration
	Post-combustion: chemical absorption method	Industrial demonstration
	Post-combustion: chemisorption method	Pilot Phase
	Post-combustion: physical adsorption method	Industrial demonstration
	Post-combustion: membrane separation method	Pilot Phase
	Oxygen-rich combustion: atmospheric pressure	Industrial demonstration
	Oxygen-rich combustion: pressurized	Research Phase
	Oxygen-rich combustion: chemical looping	Pilot Phase
Carbon Transportation	Tank truck transportation	Commercial application
	Ship transportation	Commercial application
	Pipeline transportation	Research / Pilot Phase
	Reforming for syngas production	Industrial demonstration
	Preparation of liquid fuel	Research Phase
	Synthesis of methanol	Industrial demonstration
	Preparation of olefins	Research / Pilot Phase
	Photoelectrocatalytic conversion	Research Phase
	Synthesizing organic carbonates	Industrial demonstration

Biological Utilization, Chemical Utilization	Synthesizing biodegradable polymers	Industrial demonstration / Commercial application
	Synthesizing isocyanates / polyurethanes	Industrial demonstration / Commercial application
	Preparation of polycarbonate / polyester materials	Industrial demonstration
	Steel slag mineralization utilization	Industrial demonstration
	Phosphogypsum mineralization utilization	Industrial demonstration / Commercial application
	Potassium feldspar processing combined with mineralization	Pilot Phase
	Concrete curing utilization	Pilot Phase
	Microalgae biotechnology utilization	Pilot Phase
	Gas fertilizer utilization	Research Phase
	Synthesis of malic acid	Pilot Phase / Industrial demonstration
Geological Utilization, Storage	Enhanced oil recovery	Industrial demonstration
	Coalbed methane displacement	Pilot Phase / Industrial demonstration
	Enhanced natural gas recovery	Research Phase
	Enhanced shale gas recovery	Research Phase
	Hydrate displacement	Research / Pilot Phase
	In-situ leaching mining	Commercial application
	Heat recovery	Research Phase
	Enhanced deep saline water exploitation and storage	Pilot Phase

8. Conclusion

2020 marked a significant year for CCUS in China. In September of that year, China announced its commitment to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. CCUS was identified as a crucial technology for achieving deep decarbonization in China.

Given that China's current energy structure is still dominated by fossil fuels, China offers a vast potential market for the advancement and implementation of CCUS technology. The IEA anticipates that China will become the world's largest CCUS market by 2040. The CCUS market in China is expected to surpass CNY 20 billion (USD 2.86 billion) per year by 2025 and CNY 330 billion (USD 47.14 billion) per year by 2050.

Prior to 2020, CCUS technology in China was mainly in the experimental and demonstration stages. Since then, substantial advancements have been made in CCUS technology development, which resulted in the successful completion of the first large-scale project (The Qilu-Shengli Oilfield CCUS) in February 2022. Additionally, several other projects are presently underway. Nonetheless, despite these notable accomplishments, CCUS development in China still falls short of its ambitious carbon neutrality objectives. Insufficient CCUS-related facilities, lack of large-scale projects, and technology gaps relative to international standards are among the key challenges that China must address to fulfill its climate commitments.

International cooperation is a crucial component of China's CCUS development strategy, and the country has been actively engaged in various CCUS collaborative initiatives with foreign governments and international organizations. As a leader in CCUS technology, the U.S. possesses an extensive industrial system with stringent technical standards and governmental regulations that have fostered a thriving CCUS industry and cutting-edge technological capabilities. The U.S. has incubated and nurtured outstanding companies at every stage of the CCUS supply chain. The successful industrialization and commercialization of CCUS in the United States has created substantial business opportunities for both China and the United States.

Given the long history of CCUS collaboration between China and the U.S., as well as China's rapidly expanding carbon neutrality market, it is mutually beneficial for commercial and climate cooperation in the CCUS sector between the two nations. As noted before, China is lagging behind in certain CCUS technologies, and collaboration in specific fields can help accelerate progress. Below are some potential areas of collaboration:

- Post-combustion chemical absorption: This technology involves capturing CO_2 from flue gas emissions using a liquid solvent. Collaboration could include sharing knowledge and expertise in solvent development and optimization, as well as process design and operation.

- Post-combustion membrane separation: This technology involves using a membrane to separate CO_2 from flue gas emissions. Collaboration could focus on developing and optimizing the membrane materials and designing efficient separation processes.

- Pipeline transportation: Once CO_2 is captured, it needs to be transported to a storage site. Collaboration could involve sharing knowledge and expertise in pipeline design and construction, as well as operation and maintenance.

- Enhanced oil recovery: CO_2 can be injected into oil fields to enhance oil recovery. Collaboration could focus on developing and optimizing the injection process and monitoring CO_2 storage to ensure it remains secure.

- Enhanced gas recovery: Similarly, CO_2 can be injected into gas fields to enhance gas recovery. Collaboration could focus on developing and optimizing the injection process and monitoring CO_2 storage.

- Deep saline formation sequestration: This technology involves injecting CO_2 deep underground into saline formations for long-term storage. Collaboration could focus on developing and optimizing the injection process and monitoring CO_2 storage.

- Direct air capture technologies: DAC can help achieve carbon neutrality or negative emissions by directly removing CO_2 from the atmosphere. Collaboration is important for advancing research, sharing knowledge, and driving innovation to improve efficiency, scale, and cost-effectiveness. Collaboration can also leverage public-private partnerships and multidisciplinary approaches to accelerate progress and achieve widespread adoption of DAC technologies.

In addition, there are excellent opportunities for collaboration within the supply chains of CCUS technologies, with a focus on developing and manufacturing key CCUS equipment and components. It is also advisable to undertake joint CCUS demonstration projects between the United States and China and establish a collaborative US-China CCUS hub.

Overall, collaboration is essential to accelerate the development and deployment of CCUS technologies. By sharing knowledge and expertise, countries can work together to address the global challenge of climate change.

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