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REVIEW PAPER

Carbon geological utilization and storage in China: current status and perspectives

Heping Xie · Xiaochun Li · Zhiming Fang · Yufei Wang · Qi Li · Lu Shi · Bing Bai · Ning Wei · Zhengmeng Hou

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Abstract As an emerging technology with the potential to enable large-scale utilization of fossil fuels in a low-carbon manner, carbon capture, utilization and storage (CCUS) is widely considered to be a strategic technology option to help reduce CO_2 emissions and ensure energy security in China. In principle, CCUS can be divided into three categories, namely chemical utilization, biological utilization and geological utilization. Of the three categories, carbon geological utilization and storage (CGUS) technology has obtained the most attention lately due to its ability to utilize underground resources and conditions, to generate further economic benefits, a feature that distinguishes it from other CO_2 reduction technologies. The CGUS technology related in this paper has various types, each with its own potential, difficulties and characteristics. This paper summarizes China's research findings on the various types of CGUS technology, analyzes their research status, development potential, early opportunities and long-term contributions and recommends major geological utilization methods to policy makers and investors based on China's natural resources and industrial characteristics. Besides, this paper analyzes the status, mechanisms and limitations of China's relations with other countries in this field, as a means to promote research cooperation on an international level.

Keywords Carbon geological utilization and storage (CGUS) · Carbon mineralization utilization (CMU) · China · Current status · Enhanced oil recovery (EOR) · Enhanced coalbed methane (ECBM) · Enhanced gas recovery (EGR) · Enhanced shale gas (ESG) · Geothermal systems (EGS) · Perspective

1 Introduction

China has become the world's largest energy user, consuming 20 % of the world's primary energy, including 47 % of coal and 10 % of oil [8]. Seventy percent of its electrical energy supply today is generated from coal. Even if China attains its goals of improving energy efficiency, as well as increasing the use of its renewable energy by 2030, over half of its energy production will still predominantly rely on coal [37]. According to the IEA estimates, without effective measures to reduce greenhouse gas (GHG) emissions, by the year 2030, China's energy consumption and CO_2 emissions will have doubled the levels in 2006, accounting for 23 and 29 % of the world's energy consumption and CO_2 emissions, respectively [29].

H. Xie
Center of CCUS and CO2 Mineralization and Utilization,
Sichuan University, Chengdu 610065, China

X. Li (✉) · Z. Fang · Q. Li · L. Shi · B. Bai · N. Wei
State Key Laboratory of Geomechanics and Geotechnical
Engineering, Institute of Rock and Soil Mechanics, Chinese
Academy of Sciences, Wuhan 430071, Hubei, China
e-mail: xcli@whrsm.ac.cn

Y. Wang
Key Laboratory of Energy Engineering Safety and Mechanics on
Disasters, The Ministry of Education, Sichuan University,
Chengdu 610065, China

Z. Hou
Institute of Petroleum Engineering, Clausthal University of
Technology, Clausthal-Zellerfeld, Germany

Z. Hou
Sino-German Energy Research Center, Sichuan University,
Chengdu 610065, China

In order to address the global climate change, fulfill social responsibilities, and achieve a low-carbon and sustainable economic development, China has set a goal of cutting its CO_2 emissions intensity (i.e., emission per GDP) in 2020 by 40–45 % based on the 2005 level. China has also developed and implemented a number of plans on energy conservation and emission reduction. At the Durban Climate Change Conference, China announced its intention to participate in a legally binding treaty on climate change after 2020, under five conditions: new carbon-cutting pledges by rich nations in the second commitment period under the Kyoto Protocol; fast launch of the Green Climate Fund agreed on in Cancun under a supervisory regime; implementing the consensus of adaptation; technology transfer, transparency, capability building and other points agreed upon in the former conferences as well as appraising developed countries' commitment during the first period of the Kyoto Protocol.

Although China has promised to reduce carbon intensity, its rapid industrialization and urbanization will surely lead to a further increase in the absolute carbon emissions for a long time. According to the study conducted by China's Energy Research Institute, National Development and Reform Commission, under the low-carbon scenario promised by Chinese government, China's total carbon emissions will peak in 2035 and decline rapidly thereafter. However, according to the baseline scenario, the peak year will be 2045 [1], so the emission reduction pressure in China is simple to predict.

Carbon capture, utilization and storage (CCUS) technology is considered to be an effective measure to realize large-scale CO_2 emission reduction. China stresses the importance of this emerging technology in several science and technology policy documents and gives the development of associated technologies positive guidance. *The National Medium- and Long-Term Program for Science and Technology Development plan* (2006–2020) proposes the idea of "developing fossil fuel utilization technology that integrates efficient, clean and near-zero CO_2 emissions" in the key research field of advanced energy technology; *China's Scientific and technological Special Actions on Climate Change* specifies that it is essential to develop CCUS technology for controlling GHG emissions and mitigating climate change. The *12th Five-Year Plan for Science and Technology Development* released in July 2011, stresses twice the need to develop CCUS technology in the "Energy Conservation and Environmental Protection Industry" and "Address Climate Change" sections [14].

In order to promote the CCUS research and development activities, the Social Development Technology Division under China's Ministry of Science and Technology and the Administrative Center for China's Agenda 21 released *China's CCUS Technology Roadmap* in September 2011. It proposes the vision for China's CCUS technology development: to provide technically feasible and economically affordable technology choices to alleviate climate change, and to promote sustainable economic and social development. The Roadmap indicates that CCUS may become an important strategic choice in China's future plan to reduce CO_2 emissions and ensure energy security. It also proposes deliverables at each stage of development, from the present until the year 2030.

In principle, CCUS technology may be divided into three categories, namely chemical utilization, biological utilization and geological utilization. The geological utilization technology may further be subdivided into several forms, each with different potential, difficulties and characteristics. This paper aims to summarize China's research findings on various geological utilization methods, analyze their development potential, and recommend major geological utilization methods to policy makers and investors based on China's natural resources and industrial characteristics. Besides, this paper also analyzes the status, mechanisms and limitations of China's cooperation with foreign countries in this field, which can help promote joint research on an international level.

2 Carbon geological utilization and storage technology

Carbon geological utilization and storage (CGUS) belongs to the wide scope of CCUS technology. Specifically, it refers to the process of utilizing underground minerals and conditions to mineralize CO_2 or to enhance recovery of valuable products, thereby reducing CO_2 emissions more than other CO_2-free technologies. The utilization of underground resources and conditions, an additional economic benefit, is a major feature that distinguishes CGUS from other CO_2 reduction technologies. Based on this definition, CGUS technology is mainly applied to enhance the recovery of oil (CO_2-EOR), coalbed methane (CO_2-ECBM), geothermal systems (CO_2-EGS), natural gas (CO_2-EGR), shale gas (CO_2-ESG) and carbon mineralization utilization (CO_2-CMU). These are only a few forms of CGUS technology, as further new types are likely to appear with the diversity of geological conditions and underground resources. The technologies mentioned in this paper are only those that have reached a certain level of research. Although these technologies belong in the category of CGUS, each has its own characteristics and principle features:

2.1 CO_2-EOR

CO_2-EOR is a technique that injects high-purity CO_2 into an oil reservoir in order to drive crude oil toward the production well and eventually facilitates an increase in oil production

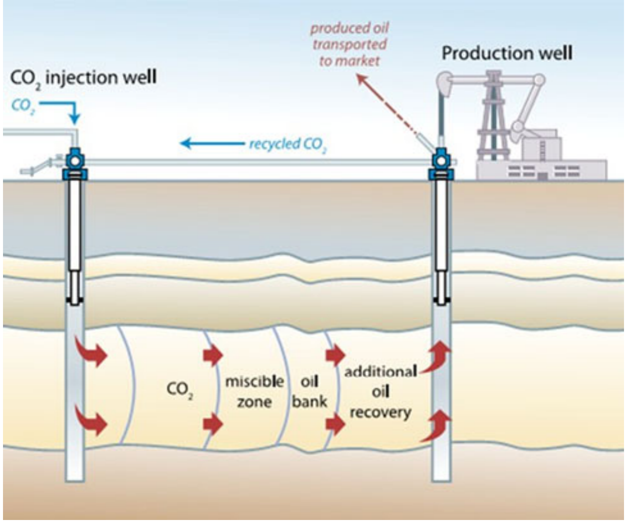

Fig. 1 Schematic of an EOR operation [44]

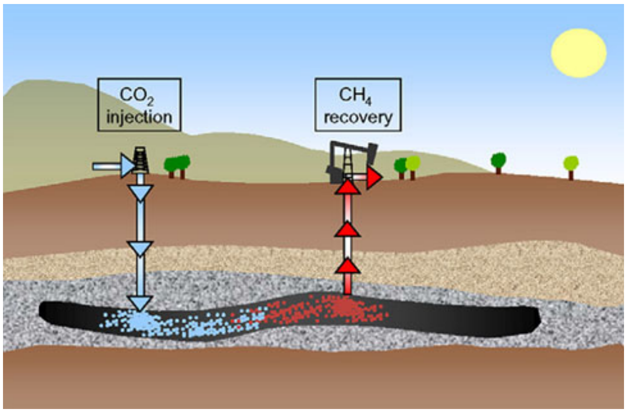

Fig. 2 Schematic of an ECBM operation [43]

by using the characteristics of CO$_2$, such as dissolution, extraction and swelling [58]. CO$_2$-EOR is proving to be one of the most efficient EOR techniques among various kinds of tertiary oil recovery technologies [7, 41] (Fig. 1).

2.2 CO$_2$-ECBM

CO$_2$-ECBM is a process whereby CO$_2$ is injected and stored in a deep, unmineable coalbed to reduce GHG emission, meanwhile displacing coalbed methane (CBM) from coal seams. It not only reduces the emissions of the greenhouse gases, but also greatly enhances the recovery of CBM. This win–win result gets extensive attention (Fig. 2).

2.3 CO$_2$-EGS

Enhanced geothermal systems (EGS) refer to artificial, thermal systems that use water as a working medium to recover geothermal energy from low permeable, hot-dry-rocks (usually 3–10 km underground; Fig. 3). Since the hot-dry-rocks in EGS have significantly low permeability, artificial stimulation is usually required to improve the production. CO$_2$-EGS is a novel EGS technique which replaces water with supercritical CO$_2$ as the working medium. This technology not only takes advantage of the special properties of supercritical CO$_2$ to improve the overall efficiency of the traditional EGS, it can also simultaneously sequester CO$_2$. In comparison with the other kinds of carbon geological utilization techniques, CO$_2$-EGS recovers green energy and theoretically causes no direct CO$_2$ emission during secondary utilization. Therefore, CO$_2$-EGS's contribution to carbon reduction embodies two aspects, that is, increasing the recovery percentage of green energy and geologically storing CO$_2$.

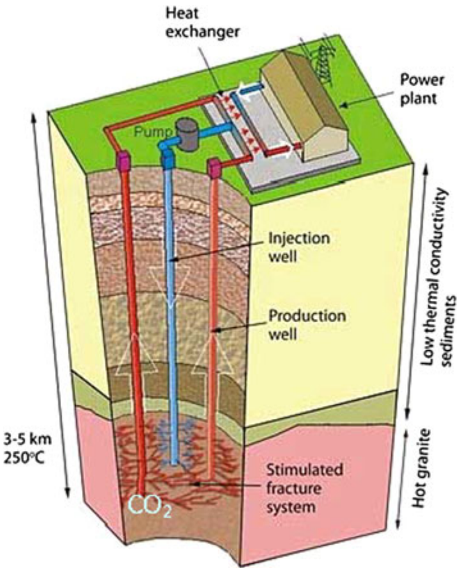

Fig. 3 Schematic of an EGS operation, modified from [72]

2.4 CO$_2$-EGR

CO$_2$-EGR is a technique that injects CO$_2$ into a depleted gas reservoir in order to enhance natural gas recovery and sequester CO$_2$ into the geological formations. Due to its potential to enhance natural gas recovery, CO$_2$-EGR can bring additional revenue from hydrocarbons, thereby reducing the overall cost of CO$_2$ capture and sequestration. Therefore, CO$_2$-EGR is a technique that is a possible candidate for early large-scale deployments (Fig. 4).

2.5 CO$_2$-ESG

CO$_2$-ESG is a technique that drives out and displaces shale gas by injecting CO$_2$ into a shale stratum to increase the recovery efficiency of shale gas, meanwhile sequestering

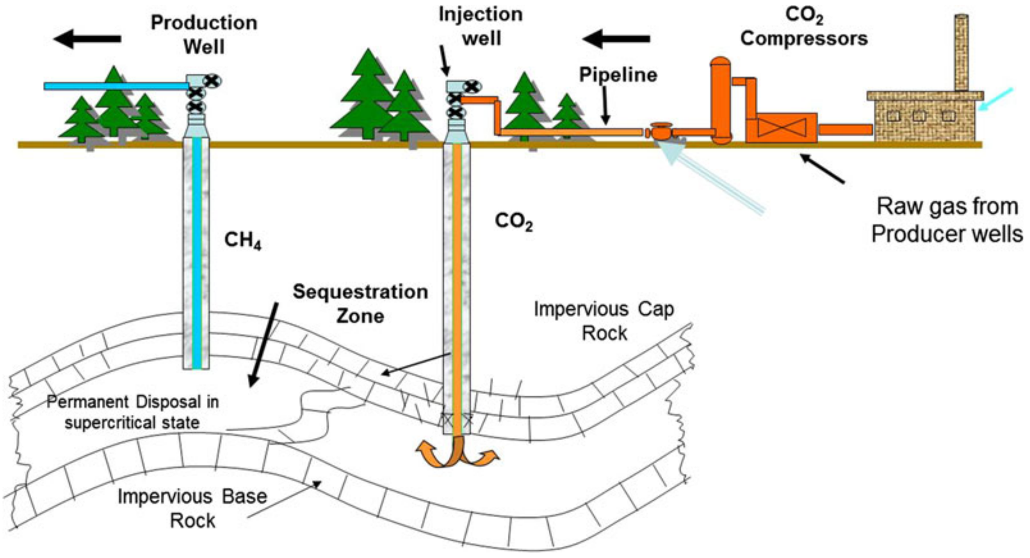

Fig. 4 Schematic of a CO_2-EGR operation redrawn from [2]

the CO_2 in the reservoir. This chiefly takes advantages of the excellent ability of CO_2 to flow through the micropores and fissure while being adsorbed onto the shale matrix. The mechanisms of CO_2-ESG are very similar to those of CO_2-ECBM [49].

2.6 CO_2-CMU

CO_2-CMU is a technique that utilizes underground natural minerals to mineralize CO_2 into stable solid carbonates. Meanwhile, valuable chemical by-products are obtained in the process [67, 68]. Due to the existence of a large variety of natural minerals, the CO_2-CMU methods are mainly selective in effect as mentioned in the following sections.

2.6.1 *CO_2 mineralization by K-feldspar and recovery of potassium salt as a by-product*

As one of the major feldspar minerals, K-feldspar can be utilized to mineralize CO_2. This reaction process will not only cause the reduction in CO_2 emissions but also enable the creation of abundant amounts of soluble potash, a raw material recovered for the production of potash fertilizers. Natural potash feldspar can mineralize CO_2 under natural condition, but the process is extremely slow, taking hundreds even thousands of years [70]. However, this can be accelerated by adding calcium chloride, applying a high temperature or introducing a catalyst, which can destroy the stable, crystalline structure of K-feldspar, making it become highly reactive to mineralize CO_2 into a stable calcium carbonate compound and recover the potassium salt within a relatively short period of time [69].

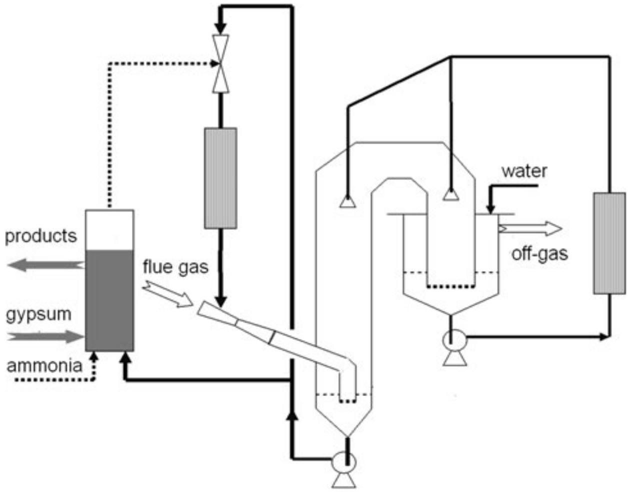

Fig. 5 Illustration of the "One step" method to mineralize CO_2 in flue gas using phosphogypsum

2.6.2 *CO_2 mineralization by gypsum and the production of a sulfur-based compound as a by-product*

Gypsum is one of the major sedimentary minerals rich in sulfur. CO_2 mineralization can be effected by using gypsum, ammonia and CO_2 as raw materials. During the process, ammonia and CO_2 will react to form ammonium carbonate, which in turn reacts with the gypsum to form calcium carbonate, a raw material for the production of the high value-added ammonium sulfate fertilizers. Recent studies have revealed that CO_2 can be mineralized directly in flue gas, which could effectively avoid the expensive process with captured CO_2. This method is called a "One step" method (Fig. 5) [68].

2.6.3 CO_2 mineralization by saline groundwater and the production of hydrochloric acid and magnesium carbonate as by-products

Saline groundwater abounds in magnesium chloride. CO_2 mineralization using magnesium chloride can produce the high value-added hydrochloric acid and magnesium carbonate as by-products [68]. CO_2 mineralization by magnesium chloride involves two steps: The magnesium chloride hexahydrate is heated to generate magnesium hydroxide and hydrogen chloride gas; the magnesium hydroxide is then reacted with CO_2 to generate magnesium carbonate, a solid powder. The hydrogen chloride gas is absorbed by pure water to make hydrochloric acid. The chemical reaction for the entire process can be summarized as follows:

$$MgCl_2 \cdot 6H_2O + CO_2 \rightarrow MgCO_3 + 5H_2O + 2HCl \qquad (1)$$

3 Current status of CGUS in China

In order to achieve the important strategy to reduce CO_2 emissions and ensure energy security, China has put more emphasis on research and development of various CO_2 emission reduction technologies. CGUS technology has received increasing attention in China, especially due to its win–win results of CO_2 emission reduction and economic returns. In recent years, the Chinese government has made active deployment of the CGUS research and development activities, obtaining considerable progress. Currently, the CGUS technical R&D activities in China are primarily financed by the government and carried out mainly by industrial enterprises with the joint participation of scientific research institutions and universities.

The government-supported research and development activities are mainly deployed by the Ministry of Science and Technology, National Natural Science Foundation of China, etc. During the “Tenth Five-Year-Plan” period, China’s national science and technology projects such as the Major State Basic Research Development Program of China (973 Program), the National High Technology Research and Development Program (863 Program), the National Key Technology R&D Program, etc., have worked together to ensure the systematic deployment of basic research, technology research and development, and demonstration of the CGUS technology in terms of its emission reduction potential, CO_2-EOR and geological storage, with respect to different emission sources, different capture methods, different CO_2 conversion and utilization methods, etc. The national key scientific and technological projects “Large Oil and gas Fields and Coal Seam Gas Development Projects” invested a huge amount of money to deploy the technology research and development and project demonstration of CO_2-EOR and CO_2-ECBM technologies. In addition, China actively participates in the Carbon Sequestration Leadership Forum (CSLF), Clean Energy Ministerial (CEM) meeting and other multilateral cooperation frameworks and organizes domestic research institutions and enterprises to participate in bilateral and multilateral cooperation projects. All of these can expand the capacity building in these related fields in China [14]. At present, CGUS projects self-developed by Chinese enterprises under government support are listed in Table 1.

However, various forms of the CGUS technology vary widely in their research status and technical maturity due to their differences in history of development, level of research and technical difficulty, as elaborated on in the discussion that follow.

3.1 CO_2-EOR

During its nearly 70 years of development and application overseas, CO_2-EOR has become a relatively mature technology in the oil industry, with over 100 projects currently in operation. The Project in Weyburn Oilfield in Saskatchewan, Canada, is one of the most successful examples of modern CO_2-EOR operations in the world. Production from this oilfield was started in 1954, and most of the easily extractable oil has already been produced. Therefore, the EnCana Corporation decided to inject CO_2 into the reservoir in order to enhance the oil recovery. The CO_2 comes from the natural gas production of Beulah Coal Gasification Company in Dakota, the United States. It is purified and transported to the Weyburn Oilfield through a dedicated pipeline that is 339 km long. It is predicted that in the next 20 years, at least 20 million tons of CO_2 will be injected into the oilfield to increase the yield of oil by 130 million barrels and extend the life of the oilfield by about 25 years [57].

Since the 1960s, China has mainly concentrated on CO_2-EOR technology and its applications. China has also conducted tests concerning the key technological challenges and industrial scale implementation. The country falls behind the developed world mainly due to major gaps in terms of engineering experience and a lack of accessory equipment. According to a report written in 1999 on China’s EOR potential, CO_2-EOR capacity accounts for about 13.2 % of the geological reservoir. It is also estimated that half of the 4.57 billion tons of oil in place, discovered between 1998 and 2003, is well suited for the CO_2-EOR technology. In addition, half of the 6.32 billion tons of oil recently discovered in the low permeable reservoirs cannot be effectively developed using the existing technology, but only by CO_2 injection [57].

Table 1 List of CGUS projects self-developed by Chinese enterprises under government support

Project	Technology types	Funding sources	Research types[a]	Execution time	Host and participating agencies
Utilization of greenhouse gases as resource in EOR and geological storage	EOR	Major State Basic Research Development Program of China (973 Program)	Basic research	2006–2010	China Petroleum Group Science and Technology Research Institute, Huazhong University of Science and Technology, Institute of Geology and Geophysics, CAS, China University of Petroleum, Beijing
Jilin Oilfield CO_2-EOR research and demonstration	EOR	Independent demonstration projects	Technology demonstration	2007	Jilin oil field
Basic research of the transport properties of CO_2, water and crude oil in dense porous media	EOR	National Natural Science Foundation of China	Basic research	2008–2011	Dalian University of Technology
Key technology research of CO_2-EOR and sequestration	EOR	National High Technology Research and Development Program (863 Program)	Technology demonstration	2009–2011	China Petroleum Group Science and Technology Research Institute, China Petroleum and Chemical Group Institute of exploration and development, etc.
Influencing factors and mechanism of CO_2 diffusion in porous media	EOR	National Natural Science Foundation of China	Basic research	2009–2011	China University of Petroleum, Beijing
Shengli Oilfield CO_2 capture and EOR demonstration	EOR	Independent demonstration projects	Technology demonstration	2010	Shengli Oil Field
Basic research of CO_2 emission reduction, storage and resource utilization	EOR	Major State Basic Research Development Program of China (973 Program)	Basic research	2011–2015	China Petroleum Group Science and Technology Research Institute
Key technologies of CO_2-EOR and sequestration	EOR	National key scientific and technological projects "Large Oil and gas Fields and Coal Seam Gas Development Projects"	Basic research	2011–2015	China Petroleum Group Science and Technology Research Institute, PetroChina Jilin Oilfield Company, etc.
CO_2-EOR and sequestration demonstration in Songliao Basin	EOR	National key scientific and technological projects "Large Oil and gas Fields and Coal Seam Gas Development Projects"	Technology demonstration	2011–2015	PetroChina Jilin Oilfield Branch Company, China Petroleum Group Science and Technology Research Institute
QSAR study on thermodynamic properties and transfer properties of CO_2-EOR system	EOR	National Natural Science Foundation of China	Basic research	2012–2014	Tianjin University
Study on the damage mechanism of CO_2-EOR process	EOR	National Natural Science Foundation of China	Basic research	2012–2015	China University of Geosciences, Beijing
Technology development and demonstration of CO_2 capture, EOR and storage from large-scale coal-fired power plant flue gas	EOR	National Key Technology R&D Program	Technology demonstration	2012–2016	Sinopec Shengli Oilfield Branch Company, Institute of Rock and Soil Mechanics, CAS, Peking University
Interfacial properties research of CO_2 capture by alcohol amine and supercritical CO_2-EOR process	EOR	National Natural Science Foundation of China	Basic research	2012–2016	North China Electric Power University, Baoding
Demonstration project of CO_2 capture and EOR from coal gasification	EOR	Independent demonstration projects	Technology demonstration	Planning	Shengli Oil Field

Table 1 continued

Project	Technology types	Funding sources	Research types[a]	Execution time	Host and participating agencies
CO_2 enhanced coalbed methane and storage	ECBM	International Cooperation projects of MOST	Basic research	2002–2007	China United Coalbed Methane Corporation. LTD (CUCBM)
Study on multi-component gas adsorption/desorption mode and mechanism of CO_2-ECBM	ECBM	National Natural Science Foundation of China	Basic research	2003–2005	China University of Mining and Technology, Beijing
Potential and basic scientific problem study on CO_2-ECBM in China	ECBM	100 Talents Programme of The Chinese Academy of Sciences	Basic research	2005–2009	Institute of Rock and Soil Mechanics, CAS
Improved model of CO_2 injection and CH_4 recovery	ECBM	National Natural Science Foundation of China	Basic research	2007–2008	China University of Mining and Technology
Effects of matrix property on coal swelling and CO_2/CH_4 permeability change in the process of CO_2-ECBM	ECBM	National Natural Science Foundation of China	Basic research	2007–2009	Institute of Coal Chemistry, CAS
Experimental study on different swelling effects of coal matrix in the process of CO_2-ECBM	ECBM	National Natural Science Foundation of China	Basic research	2008–2010	China University of Mining and Technology, Beijing
Applied basic research of CO_2-ECBM in deep unmineable low permeability coalbeds under solid-flow-thermal coupling conditions	ECBM	National Natural Science Foundation of China	Basic research	2009–2011	Liaoning Technical University
Solid–gas interaction and storage experimental simulation of CO_2-ECBM in deep coalbeds	ECBM	National Natural Science Foundation of China	Basic research	2010–2012	Institute of Process Engineering, CAS
Potential and suitability assessment of CO_2-ECBM in China	ECBM	Projects of Center for Hydrogeology and Environmental Geology Survey, CGS	Basic research	2011	Institute of Rock and Soil Mechanics, CAS
Study on the binary gas–solid coupling and dual porosity effect in the process of CO_2-ECBM in deep coalbeds	ECBM	National Natural Science Foundation of China	Basic research	2011–2013	China University of Mining and Technology
Study on the migration law and permeability enhance mechanism in the process of supercritical CO_2 inject into low permeability coal seams	ECBM	National Natural Science Foundation of China	Basic research	2011–2013	Liaoning Technical University
Research on Deep coal seam CO_2 Injection/Storage to Enhance Coalbed Methane Recovery	ECBM	International Cooperation projects of MOST	Basic research	2011–2015	China United Coalbed Methane Corporation, LTD (CUCBM)
Study on the thermal-flow-solid interaction mechanism of CO_2-ECBM	ECBM	National Natural Science Foundation of China	Basic research	2012–2014	China University of Mining & Technology
Study on the mechanisms of N_2/CO_2 mixed gases enhanced coalbed methane and the best gas component ratio	ECBM	National Natural Science Foundation of China	Basic research	2012–2014	Institute of Rock and Soil Mechanics, CAS
Interaction between supercritical CO_2 and coal and its effect on CO_2 storage in the process of CO_2-ECBM	ECBM	National Natural Science Foundation of China	Basic research	2012–2015	Shandong University of Science and Technology

Table 1 continued

Project	Technology types	Funding sources	Research types[a]	Execution time	Host and participating agencies
Simulation and prediction of CO_2-EGS	EGS	Ph.D. Programs Foundation of Ministry of Education of China	Basic research	2011–2013	Jilin University
Basic research of application of CO_2 in unconventional oil and gas reservoirs development	ESG	Key program of the National Natural Science Foundation	Basic research	2011–2014	China University of Petroleum
Study on large-scale CO_2 utilization and storage technology in the novel EGS	EGS	International Cooperation Project of MOST	Basic research	2012–2014	Tsinghua University, the Administrative Center for China's Agenda 21, Institute of Rock and Soil Mechanics, CAS, Chinese Academy of Agricultural Sciences
Study on synthetic utilization and development of "Hot Dry Rock"	EGS	National High Technology Research and Development Program (863 Program)	Basic research	2012–2015	Jilin University, Tsinghua University, Tianjin University, Guangzhou Institute of Energy Conversion, CAS, PetroChina, Institute of Rock and Soil Mechanics, CAS, etc.
Study on the interaction between CO_2/CH_4 and rock mass in the process of ESG	ESG	National Natural Science Foundation of China	Basic research	2013–2015	Chongqing University
Study on new methods and new technologies of CCUS	CMU	Henhua Group Corporation Limited project	Basic research	2011–2012	Sichuan University, Henhua Group Corporation Limited
Research and development of CO_2 mineralization utilization	CMU	National Key Technology R&D Program	Technology demonstration	2012–2015	Sichuan University, China Petroleum and Chemical Corporation

[a] "Research types" include the following: basic research, technology demonstration, industrial operation and commercial application. Among them, basic research refers to theoretical research and technology development indicated the completion of a pilot test of the whole process (less than 10 % of the industrial scale); technology demonstration refers to the completion of a demonstration of the whole process (10–50 % of the industrial scale); industrial operation refers to the whole process (50–100 % of industrial the scale); commercial application refers to the operation of multiple whole process industrial plants

In 2009, the Daqing Oilfield incorporated CO_2-EOR technology into its strategic technical arsenal. They gradually expanded their capacity to use CO_2 injection from an initial testing area on peripheral oilfields to previously defunct ones. A stock of 370 million tons of oil in the low permeability reservoir in Fuyang, which is located on the periphery of Changyuan, Daqing, which cannot be extracted by conventional water injection technology, provides a lot of latitude for tackling key problems associated with CO_2-EOR technology. The Changling gas field operated by PetroChina Jilin Oilfield Company was completed and put into operation at the end of 2009. It now possesses a comprehensive production capacity of 1 billion cubic meters of natural gas per year. This is China's first project that integrates natural gas production, CO_2 storage and CO_2-enhanced oil recovery. Dagang Oilfield uses CO_2-EOR to revitalize the old Kongdian area, which, although once decommissioned, now achieves a daily yield of over 3 tons, with its watercut reduced from 90 to 60 % [7]. Shengli Oilfield is currently building China's largest set of devices used for the capture and purification of flue gases from coal-fired power plants in the Shengli Power Plant. It is expected to reduce CO_2 emissions by over 30 thousand tons and enhance oil recovery by 20.5 % per year, when completed. In 2006, a trial run of Sinopec's key research project—CO_2-enhanced recovery of a low permeability oil reservoir—was carried out in Zhongyuan Oilfield. An attempt was made to capture CO_2 from refinery flues as an oil-displacing agent for tertiary oil recovery. In April 2010, the trial run made a significant breakthrough. In the Second Oil Production Plant of Zhongyuan Oilfield, over 217 thousand tons of CO_2 and 82.4 thousand cubic meters of water were injected, contributing to a total oil increase of 3.6 thousand tons in the three corresponding oil wells. Among them, the Pu-1-67 well increased daily crude oil production from 0.1 ton to 9.6 tons, with a maximum of 13.2 tons and a water-cut reduction of 22.3 % [57].

As a relatively mature technology, CO_2-EOR is no longer technically challenging for the petroleum industry, except for further enhancing economic benefits [54]. EOR processes have multiple advantages: mature technology; extra economic returns; provable safety of gas sequestration. The disadvantages are: a complex process; limitations on the quantity and location of gas injection; the safety problem of abandoned well; undiscovered fracture during oilfield exploitation [3, 5, 22, 42, 61, 62].

3.2 CO_2-ECBM

The study of CO_2-ECBM started overseas in the early 1990s. Numerous research studies reveal the significance of CO_2-ECBM for storing CO_2 and enhancing CBM production. However, at present, field tests conducted around the globe show considerable variations in results, suggesting site dependence and the low maturity of this technology.

Universities and scientific research institutions in China started research on CO_2-ECBM in the late twentieth century. These studies mainly focus on basic theories, such as the differences in the adsorption, swelling and flow characteristics of CO_2 and CH_4 on different coal rocks [19, 20].

ECBM field tests in China are largely conducted by the China United Coalbed Methane Corporation, LTD (CUCBM). China has so far conducted a single-well field test (2002–2007) in cooperation with Canada, in an Anthracite coal seam, located in the in Southern Qinshui Basin, to study the feasibility of ECBM in Chinese coal seams. According to the research results, CO_2 injection in this area can enhance the recovery of CBM and simultaneously possess the potential of CO_2 storage [75].

Currently, under the support of Ministry of Science and Technology and, based on the successes of the previous Sino-Canada cooperation, CUCBM is carrying out the "Research on Deep coal seam CO_2 Injection/Storage to Enhance Coalbed Methane Recovery" project. In April 2010, CO_2 injection test was conducted to study CO_2 absorption/desorption characteristics of coal, combining laboratory studies and field tests. This field test will help the research and development of the technology to inject CO_2 into deep coal seams for CBM recovery.

Considering the low permeability of coal seams in China, the primary research and development direction to achieve large-scale implementation of ECBM technology is to develop well completion as well as permeability enhancement and process control technologies. China Huaneng Group is preparing to carry out ECBM trials in Yunnan and Shanxi, respectively, to conduct research on related technologies.

3.3 CO_2-EGS [23, 52, 77, 78]

EGS started in Los Alamos National Laboratory in the 1970s, and was later studied in the United States, Japan, Europe, Australia and other developed countries. Water had remained the heat-transfer working medium in early EGS systems until 2000 when Brown noticed CO_2 has chemical and physical properties that are preferable for operating an EGS system. A new concept of using CO_2 instead of water as working medium was proposed, which can reduce direct CO_2 emission, meanwhile bringing extra returns. In 2004, Fouillac et al. also mentioned that CO_2 possesses favorable geochemical characteristics as a heat-transfer medium as it can be easily captured and stored by minerals and rocks. In 2006, Pruess and Azaroul preliminarily evaluated the effect of CO_2 as a heat-transfer medium and confirmed Brown's idea. Currently, more basic research on the mechanisms and advantages of CO_2 as a heat-transfer medium are being carried out. Recently, the University of Queensland has set up a Geothermal Energy Utilization Center to develop EGS technologies based on CO_2. This is a brief account of the development of CO_2-EGS technology, overseas.

In China, the development of geothermal energy is based on the direct utilization of medium to low temperature geothermal resources. EGS is receiving more and more attention. Both the national and local governments have already started to formulate plans for research, development and resource evaluations of the geothermal energy of hot-dry-rocks. Several enterprises specializing in hot-dry-rock geothermal energy development have already been set up. In recent years, the Chinese Academy of Sciences, universities, design institutes and other institutions have also started research, mainly focusing on the basic research aspects, such as the exploration and evaluation of technologies, EGS mechanisms, interactions between EGS flow and heat reservoir, heat-transfer mechanism and energy conversion technology, etc. Although China has geothermal wells more than 4,000 m deep, and Yangbajain in Tibet has drilled to the hot-dry-rock formations, yet demonstration projects are still few and farther apart. The research work into EGS with CO_2 is just at the fledgling stage with too little initial investment. Currently, there are only three basic research programs (See Table 1) in progress. Most of the knowledge on China's localized CO_2-EGS has been left untouched.

3.4 CO_2-EGR

Currently, the world's CO_2-EGR is still at the stage of systematical evaluation and demonstration with its pilot and demonstration projects merely in a fledgling state. In the Netherlands, the K12-B project was carried out to store CO_2 in depleted oilfields. This project injected over 60 thousand tons of CO_2 during 2004–2009 [26, 65] (URL: http://www.k12-b.nl/). Enterprises and research institutions from Australia, Norway and other countries are also doing research on CO_2-EGR [4, 6, 16, 25, 34, 38, 40, 51, 55, 60, 63].

The preliminary theoretical estimation of the storage capacity of CO_2 in depleted gas fields in China is 5.18Bt [35]. Since CO_2-EGR shows certain potential in enhancing natural gas recovery and contributes additional revenue from hydrocarbon by-products, it has the possibility of cutting down the overall costs of CO_2 capture and storage. It is an option with opportunities built-in at the onset. However, the timing is not good for industrial scale deployment of CO_2-EGR, in China, as there seem to be still very few depleted natural gas fields at present to warrant profitable exploitation.

3.5 CO_2-ESG

Extraction of free or adsorbed shale gas from organic-rich shale and interlayer dates back to 1821 when shale gas was first extracted from the Appalachian Basin in the United States. However, due to the tightness and low permeability of shale, progress in shale gas recovery was very slow before the twenty-first century [10, 39]. Recently, the United States has made a significant technological breakthrough in the exploration and exploitation of shale gas, resulting in a remarkable increase in production. This exerts a huge impact on the natural gas market as well as the global energy structure and prompts resource-rich countries to increase their efforts in the field. In 2012, China released its National Plan for the development of shale gas (2011–2015) which aims to promote the exploration and exploitation of shale gas, increase gas energy supply, adjust the energy structure and reduce green house gas emissions.

Adsorbed shale gas takes up 20–80 % of the reservoir [10, 39, 76], which leads to low production rates for single-wells, low recovery rates and a long production cycle in shale gas recovery. Since supercritical CO_2 is a highly mobile and adsorptive fluid in shale reservoir [12, 47] and already successfully applied in ECBM and EOR, the idea of using it to enhance shale gas recovery naturally stands out [44, 49, 56, 66]. Moreover, adsorption of CO_2 during natural gas recovery can help in reducing CO_2 emission [9].

Currently, CO_2-ESG is still in the exploratory stage in China. In 2010, NSFC set up a project for basic research on supercritical CO_2-enhanced nonconventional gas recovery.

3.6 CO_2-CMU

At present, there is a lot of research on CO_2 mineralization all over the world. Silicate minerals, such as olivine, serpentine, wollastonite, etc., have often been studied as reactants for mineralization of CO_2 [13, 17, 27, 28, 30, 32, 33, 45, 48, 50, 64]. The cost of CO_2 mineralization using silicates is exorbitantly high, but this is compensated for by the production of valuable by-products in the process. Hence, at the moment, the research on CO_2 mineralization is only possible in laboratory experiments and field tests.

Table 2 Technical maturity of each CGUS technology

Type of CGUS technology	Basic research	Technology demonstration	Industrial operation	Commercial application
EOR		√		
ECBM	√			
EGS	√			
EGR	√			
ESG	√			
CMU	√			

CO_2 mineralization utilization (CMU) was first proposed by the author of this paper as a way to reduce CO_2 emissions and produce valuable products. Although the idea is still at the laboratory and field test stage, it is developing fast and it is strongly supported by the government. Sichuan University and Sinopec are together planning to launch the world's first industrial demonstration project in Dazhou, Sichuan. This project will use gypsum to mineralize CO_2 so as to produce a sulfur-based compound as a by-product. The design of a pilot-scale test of CO_2 mineralization using K-feldspar and the recovery of potash fertilizer as a by-product is also in progress. Though CO_2-CMU has a good potential for sequestering CO_2, it is necessary to further reduce energy consumption in order to realize efficient CO_2 mineralization and resource extraction with low energy and cost consumption.

Based on the above analysis, the level of technical maturity for each variety of CGUS technology in China can be assessed as shown in Table 2.

According to the above analysis, it can be concluded that the levels of development for the various forms of CGUS technology are quite uneven. In general, the development status of CGUS technology in China may be characterized as follows: (1) EOR has the longest history of development and is relatively mature. Basically, there will be few technical barriers to large-scale implementation if CO_2 capture technology is improved to reduce CO_2 cost to a certain level; (2) though China conducts sufficient basic research to clarify the mechanisms of ECBM, special coalbed conditions in China make it technically difficult for large-scale application, let alone commercial operation, unless there is a breakthrough in some key technologies, such as well completion, permeability enhancement and process control; (3) geothermal energy cannot compete with oil, natural gas or coal in China, relevant research is still lagging, and basically CO_2-EGS is still in its conceptual phase; (4) though it is technically feasible for an EGR demonstration, most gas fields in China are far from being depleted, making it untimely for large-scale application; (5) until recently, China had not realized the importance of shale gas as a resource and started research. Therefore, it is seriously lagging behind in research and development for the conventional recovery technology. Though ESGR is similar to ECBM in principle, the unique conditions of the shale reservoir (e.g., extremely low permeability) may make ESGR technology more difficult. Besides, relevant research and development has not yet started and still remains in the conceptual phase. (6) CMU is a newly proposed concept, and its study is still in its infancy. The technical feasibility of CMU remains unclear, but it shows huge potential and possibly low costs.

In order to integrate the relevant research and development activities, the Social Development Technology Division under China's Ministry of Science and Technology and the Administrative Center for China's Agenda 21 released *China's CCUS Technology Roadmap* in September 2011. It proposes the vision for China's CCUS technology development: to provide technically feasible and economically affordable technology choices to address climate change, and to promote sustainable economic and social development (Fig. 6). The Roadmap indicates that CCUS may become an important strategic choice in China's future plans to reduce CO_2 emissions and ensure energy security, and it also sets some milestone objectives from the present until 2030: (1) By 2015, key capture technologies with low energy consumption will be realized and R&D systems for storage safety established. The full-chain pilot and demonstration project at a scale of over 300,000 ton/year will be conducted with the aim of achieving less than 25 % additional energy consumption at a cost of about RMB 350/t; (2) by 2020, the storage safety system will be in place. The megaton full-chain CCUS demonstration will be set up with less than 20 % additional energy consumption at a cost of about RMB 300/tons; (3) by 2030, the technical and engineering capacity on design, construction and operation of full-chain CCUS project at a scale of over 1 megaton/a, less than 17 % additional energy consumption and the cost of RMB 240/t or less will be realized. In addition, the Roadmap also points out that it is necessary to pay attention to the research and development of emerging CCUS technologies and launch research on novel storage approaches and technologies, such as innovative capture technology, mineral storage, rock salt caverns storage, basalt storage, nonpure CO_2 storage, water, heat and mineral recovery through CO_2 storage, enhanced exploration of shale gas and natural gas hydrate [14].

4 CGUS potential and perspective

Most CGUS technologies are still at the basic research stage, and their early opportunities and long-term prospects are strongly influenced by policy makers, investors and researchers. Notwithstanding the uncertainties, the status of the various forms of the CGUS technology in China, including its associated early opportunity and long-term contribution, is ranked according to six factors: technical maturity, technical difficulty, theoretical emission reduction capacity, law and regulation environment, economy and security, see Table 3.

4.1 Methodology

The Chinese government has defined the emission reduction targets until the year 2020. Naturally, it is easier for technologies with an early opportunity for development to get attention. The possibility for large-scale application for these technologies depends on five factors, including technical maturity, technical difficulty, regulation environment, economy and security. The score for an early opportunity for a given form of CGUS technology is defined as the total score of the five factors divided by 20.

The long-term contribution, defined as the possibility of large-scale application of each technology when the technology is mature and the regulation environment is ready, is also an important factor that must be considered. The score for the long-term contribution of each technology is defined as the value of the total scores for theoretical emission reduction capacity, economy and security divided by 12.

The classifications and scores for technical maturity are shown in Table 3. Technical difficulty refers to the degree of difficulty in technical aspects as the technology becomes mature; theoretical emission reduction capacity is the technically feasible CO_2 sequestration capacity of the underground resources (e.g., space, minerals), regardless of the indirect emissions and market acceptance of the technology; regulation environment refers to the degree of satisfaction of the status quo with the laws and regulatory framework for the commercialization of each technology; Economy is the cost of reducing one ton of CO_2; security refers to the potential environmental risks of the geological engineering (capture, transportation and other ground industrial processes are not included).

The classification and scores for the technical maturity are shown in Table 2. The following section will introduce the evaluation and score of theoretical emission reduction capacity in detail first and then describe the score standards of technical difficulty, regulation environment, economy and security.

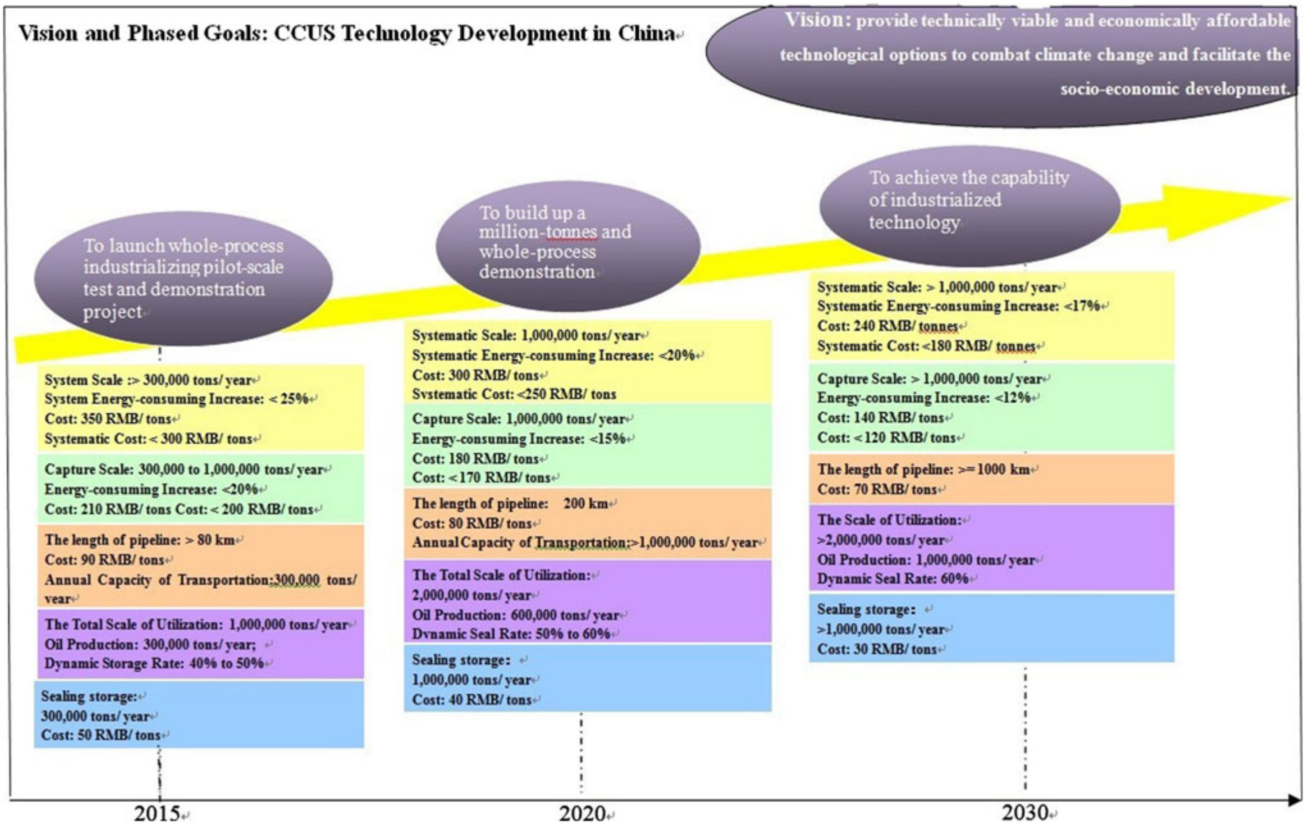

Fig. 6 Vision and phased goals for CCUS technology development in China [14]

4.2 Evaluation and score of theoretical emission reduction capacity

4.2.1 CO_2-EOR

Based on the geology and the hydrocarbon conditions of the national oilfields, Li et al. [35] estimated the capacity of carbon dioxide storage to be about 48 million tons. According to Table 3, a score of three points has been allotted.

4.2.2 CO_2-ECBM

As one of the CGUS technologies, the purpose of ECBM technology is to inject large amounts of CO_2 into the deep unmineable coal seams for long-term sequestration to achieve the GHG emissions reduction target. Therefore, the conflict between CO_2 sequestration and coal mining should be considered. That is to say the target coal seams for CO_2 storage should not be mined for an indefinite period; otherwise, the injected CO_2 will again be released in the process. As a result, it would not be possible to reduce CO_2 permanently. Currently, the mining depth of most coal seams in China is less than 1,000 m. On the other hand, there are only data for CBM resources at a depth of less than 2,000 m. Accordingly, the potential for ECBM refers to that at depths between 1,000 and 2,000 m. According to the latest national CBM resources survey, there are a total of 222,991.07 × 10^8 m^3 CBM resources at depths from 1,000 to 2,000 m, including a producible CBM resource 92,110.05 × 10^8 m^3. Based on the CO_2 storage capacity evaluation methodology recommended by CSLF, the total CO_2 storage capacity of coalbeds in China is about 100 million tons [21]. Therefore, according to Table 3, the score of theoretical emission reduction capacity in coalbeds is 3.

4.2.3 CO_2-EGS

The storage capacity evaluations for CO_2-EGS are not yet under way in China. Here, a rough methodology will be given to estimate China's storage capacity for CO_2-EGS. It is postulated that the there are two mechanism for the hot-dry-rock (HDR) to sequestrate CO_2. First is the dissolution in the micropore water and second are the reactions with the anorthite minerals in the granite rock, which is in effect a kind of mineralization storage. Thus, the estimate equation is:

Table 3 Scoring criteria for CGUS technology status

Factor	Classification	Score ranking
Technical maturity	Basic research	1
	Technical demonstration	2
	Industrial operation	3
	Commercial application	4
Technical difficulty	A number of key technical problems yet to be solved	1
	One key technical problems yet to be solved	2
	There are no key technical barriers except lack of large-scale systems integration experience	3
	There are no key technical barriers but should have large-scale systems integration experience	4
Theoretical emission reduction capacity	Theoretical emission reduction capacity $<10^8$t	1
	Theoretical emission reduction capacity $>10^8$t, $<10 \times 10^8$t	2
	Theoretical emission reduction capacity $>10 \times 10^8$t, $<100 \times 10^8$t	3
	Theoretical emission reduction capacity $>100 \times 10^8$t	4
Law and regulation environment	Unable to meet the demands of the laws and regulations	1
	No legal barriers but a lack of relevant regulations	2
	The legal and regulatory framework meets the demand	3
	The legal and regulatory framework meets the demands of commercial application	4
Economy	No benefits even with sufficient public funds	1
	No benefits of an income from carbon trading	2
	Be beneficial in a few cases even without public funds and carbon trading	3
	Be generally beneficial even without public funds and carbon trading	4
Security	CO_2 and other harmful substances from the engineering can easily escape in principle, due to a lack of control experience	1
	CO_2 and other harmful substances from the engineering can easily escape in principle, even with control experience	2
	No CO_2 and other harmful substances from the engineering, can easily escape, in principle, and control experience is available.	3
	No CO_2 and other harmful substances from the engineering can easily escape in principle	4
Early opportunity		Total scores of technical maturity, technical difficulty, regulation environment, economy and security divided by 20
Long-term contribution		Total scores of theoretical emission reduction capacity, economy and security divided by 12

$$\begin{aligned}\text{Storage capacity} = {} & \text{Mineralization capacity} \\ & (\mathbf{a} * \mathbf{b} * \mathbf{A} * \mathbf{h} * \mathbf{f} * \boldsymbol{\rho} * \boldsymbol{\beta}) \\ & + \text{Dissolution capacity } (\boldsymbol{\phi} * \mathbf{s})\end{aligned} \tag{2}$$

where **a** is the effective area coefficient, which considers that not all the geothermal fields can be used. It usually takes the value 0.1. **A** is the total area of recoverable geothermal fields ranging in depth from 3.5 to 7 km. Lin et al. [36]. Shows that the horizontal profiles at depths 3.5, 4.5, 5.5 and 6.5 km are, respectively, 1.07×10^5, 8.42×10^5, 2.10×10^6 and 3.50×10^6 km^2. **A** is the sum of these values.

h = 4 km is the total formation thickness of the geothermal fields.

b = 0.14 is the CO_2 spread coefficient.

f is the volume fraction of the mineral anorthite in the granite rock, which is estimated to be about 20 %.

$\boldsymbol{\rho} = 2.7 \times 10^3$ kg/m^3 is the density of the mineral anorthite.

$\boldsymbol{\beta}$, the reacted mass of CO_2 with unit anorthite, is 0.158 [15].

$\boldsymbol{\phi}$ is the microporosity of granite, taken as 1.2 % according to [71].

s is the solubility in water at 50 MPa pressure and 250 °C, with the value 24.8 kg/m^3 [18].

Using the model above, the estimated storage capacity of CO_2-EGS is about 78.62 × 10^2 billion tones, which according to Table 3 gives a score of 4.

4.2.4 *CO_2-EGR*

IPCC special report points out that the storage capacity of depleted gas fields can reach a magnitude of tens billion tons [44]. The preliminary evaluation of storage capacity of depleted gas fields in China is about 5, 180 million tons [35]. Therefore, the score of mitigation potential in Table 3 is 3.

4.2.5 *CO_2-ESG*

The storage potential of CO_2-ESG has not yet been evaluated and will be primarily estimated based on some existing data. The following assumptions are made: (1) adsorbed gas and free gas both account for 50 % of shale gas recoverable reserves, and CO_2 is sequestered in two forms: adsorbed gas and free gas; (2) the replacement factor of CO_2 for the adsorbed shale gas is equal to 2, while for free gas, it is 1 [47, 56]; (3) CO_2-ESG, used for recovering shale gas, takes up 10 % of the recoverable reserves. On the basis of these assumptions, the storage potential of CO_2-ESG is about 7.5 billion tons and thus gains three points according to Table 3.

4.2.6 *CO_2-CMU*

K-feldspar is an insoluble mineral, which is rich in potassium and widely distributed all over the world. In China, there is more than 60 K-feldspar mines with an average K_2O content for these minerals of about 11.63 %. Accordingly, the amount of K-feldspar which could be mined is about 7.914 billion tons in total [24]. If 80 % of these K-feldspars could be utilized for mineralizing CO_2, then CO_2 would be reduced by about 0.43 billion tons.

The mineral gypsum is widely distributed in China. Until now, more than 100 billion tons of gypsum has been detected [74]. Moreover, residual gypsum has been generated as a by-product in the production of phosphoric acid. In China, about 50 million tons of gypsum has been generated annually with the total amount of waste gypsum reaching over 500 million tons. According to the phosphorite reserves, about 5 billion tons of waste gypsum will be generated in the future. In theory, if 30 % of the natural gypsum and the whole of the waste gypsum were used to mineralize CO_2, the amount of CO_2 could be reduced by more than 9 billion tons.

In addition, China is also abundant in magnesium chloride. There are four major salt lakes in China, which are rich in magnesium chloride and have a total quantity of several billions tons. In theory, more than 1 billion tons of CO_2 could be sequestrated by using the chloride magnesium in salt lakes.

In theory, the total quantity of CO_2 which could be reduced by CMU is more than 10 billion tons, scoring 4 point in Table 3.

4.3 Score standards for the factors: technical difficulty, regulation environment, economy and security

Due to strong subjectivity, the authors and invited experts have derived a score for each of these factors based on a concrete understanding of the technological principle and development status of each factor after several consultations.

4.3.1 *CO_2-EOR*

Technical difficulty Compared with reservoirs in the United States, more complex conditions apply to Chinese reservoirs. The key reservoir characteristics of most oilfields in China include a continental sedimentary geology, strong heterogeneity, weak fluidity of crude oil, high wax content, high mixture pressure with CO_2, tectonic complex, etc. A large proportion of Chinese oilfields have low permeability (or ultra-low permeability) reservoirs and high-temperature high-salt reservoirs. Overall, the majority of the reservoirs of in the main oilfields suffer from the channel flow due to water injection in the past. All these factors have blocked the commercialization process of CO_2-EOR in China. However, the Shengli, Zhongyuan, Jiangsu, Daqing, Renqiu, Liaohe and Jilin Oilfields have launched CO_2-EOR test runs with low gas injection rates, less than 10 tons of CO_2 per year, and have achieved good results, improving the recovery factor by 10–15 %. Shengli and Jilin Oilfields especially have started a full-chain process of industrial scale projects with an annual injection rate of 50 million tons of CO_2 in complex geological conditions. This implies that CO_2-EOR has basically overcome the key technical hurdles and scores up to three points in Table 3.

Regulation environment The aforementioned CO_2-EOR projects are implemented under the legal framework of mineral resources and environmental protection and lack the long-term responsibility and incentives for reduction quotas of carbon dioxide emission. At the specification level, there is the lack of technical standards and regulatory mechanism for CO_2 pipeline transportation, HSE (Health, Safety and Environment), and measurement and certification, etc., and according to Table 3, this factor scores two points.

Economy Under the present conditions of high oil prices, some of the CO_2-EOR projects in better source-sink localities will be profitable, but most CO_2-EOR projects cannot be profitable without incentives [11]. Thus, the economic factor scores all three points.

Security There are no hazardous substances other than CO_2 involved in the underground engineering aspect of CO_2-EOR. Furthermore, the presence of oil has proved naturally the high sealing performance of the caprock, and the oil and gas industry has already acquired immense practical experience in blowout prevention and disposal technologies, and the escape risk of CO_2 is therefore small. However, in the long term, carbon dioxide is mainly in a free phase state, and as the caprock has already experienced the first and secondary recovery processes, it may develop weakness in some places, losing its integrity. Furthermore, a large number of abandoned wells may also become potential channels for CO_2 to escape. Therefore, according to Table 3, this factor scores three points.

4.3.2 CO_2-ECBM

Technical difficulty After 10 years of research, the technology has attained a considerable technical base, especially in basic theory and field experience. Although the overall level of this technology in China is still lagging behind other countries, in particular Europe and the United States, some technical aspects have reached an international advanced level. It may be more difficult to implement ECBM in China due to the very deep locations of the coal seams, low permeability and so on. However, it is stepping up to carry out studies on relevant technologies, such as well completion, permeability enhancement and process control, for the low permeability and soft coal seams. The ECBM potential has only been primarily evaluated, although some coalbed basins with an early opportunity, such as Qinshui basin and Ordos basin, have already been investigated in detail. Hence, according to Table 3, the score for technical difficulty is 2.

Regulation environment China is now making a great effort to develop CBM. Many support and incentive policies create a favorable policy environment for the implementation of ECBM technology. On the other hand, the pressure on China to control GHG emissions makes it very urgent to develop its research on ECBM technology. This is important for China to achieve both its CBM development goals and GHG emission control targets. Accordingly, the score for regulation environment is 3.

Economy There is a perfect match between the distribution of CO_2 emission sources and coalbed basins. Generally, it is possible to find several emission sources in the vicinity of a coalbed basin, and most of the emission sources can be matched well with nearby basins. Optimization of the match between sources and sinks can reduce the costs and risks caused by long-distance transportation. In addition, the average recovery factor of CBM has been increased from 41.42 to 60.32 % by the storage of CO_2 in coalbed formations, thereby increasing the production of CBM to 4.26×10^{12} m^3 [21]. This has made it more cost-competitive and attractive to implement ECBM in China. Therefore, according to Table 3, the score for the economy is 3.

Security In view of the mechanism of CO_2-ECBM, CO_2 is kept in coalbeds in the adsorption state, making it to be more secure than that in a gaseous or supercritical state. On the other hand, CO_2 is sequestrated in coalbeds deeper than 1,000 m, where the coal seams are more stable, and also it is easier to find a thick, good sealing caprock. In this case, the security factor may score higher, that is, a 4.

4.3.3 CO_2-EGS

Technical difficulty CO_2-EGS is a relatively novel technology which has not yet been deployed widely to recover geothermal energy. Most of the existing EGS demonstration projects in EU, the United States, Australia and Japan use water as the working fluid. Some unresolved knowledge gaps and technological problems continue to hinder the adoption of CO_2 as a working fluid in EGS. Under high stress and high-temperature environment, it is not very clear how CO_2 would interact with granite reservoir minerals. The comprehensive efficiency and advantage of CO_2 over water is still under study. Permeability enhancing technology is based on stimulation, low-cost well drilling technology and a high-efficiency utilization technology especially for the CO_2 exchanger systems to work with supercritical CO_2 for power generation. The GCCSI report [73] considers that the commercial use of CO_2 as a transmission fluid is still in its early stages of R&D with the technical, commercial and economic feasibility still to be tested, and therefore, this technology is unlikely to be commercialized within the next 10 years. China is one of the leading countries to study the medium to low temperature geothermal utilization. The Chinese Ministry of Land and Resources is laying out the evaluation, exploration and development plan for the HDR resource. In Tibet, a high-temperature HDR well succeeded in producing hot water. However, there is still very little experience in the EGS technology. As regards CO_2-EGS, China is still at the fundamental research stage, no CO_2-EGS pilot test has been conducted. According to Table 3, the score is 1.

Regulation environment The current development of geothermal resources is mainly following the legal framework in mineral resources, renewable energy, environmental protection, etc. China's Ministry of Land and Resources has set out a series of programs for geothermal development and the regional regulations for geothermal management have been set out by local governments. Generally, there are inadequate legislation and lack of uniform standards and planning for geothermal development and utilization. The existing technical specifications are mainly for medium to low temperature geothermal resources, and no specifications for the HDR have been set out. However, the situation is possibly changing for the better. The Ministry of Land and Resources has already declared that during the 12th 5-Year Plan, it will initialize the development and utilization work of HDR for geothermal resources. According to Table 3, the score is 1.

Economy The economy for CO_2-EGS depends on its competitiveness with other technologies and is affected by a number of uncertainties. The carbon penalty policy is beneficial for improving its competitiveness. However, the current carbon trade market may not offer a big push for CO_2-EGS. According to Table 3, the score is 2.

Security The sequestered amount of CO_2 by CO_2-EGS is the residual part of the CO_2 working in the development process. This part of the sequestered CO_2 will mainly exist in the form of mineralization and cannot be easily mobilized. In granite formations, there are no caprocks with very low permeability as in mudstones. Moreover, granite usually has a much higher elastic modulus than sedimentary rock, and hence, there is a higher possibility for inducing micro-seismicity of a higher magnitude during the CO_2 injection process.

4.3.4 *CO_2-EGR*

Technical difficulty There are some technical barriers to large-scale deployment of CO_2-EGR in China. First, compared with gas fields in USA and other counties, the properties of gas fields in China are more complex. The structural geology of gas field reservoirs is diverse and quite complex, while the geology of natural gas reservoirs is predominantly nonmarine sandstone of low permeability and marine carbonate formations with a complex fracture system. The reservoirs are characterized by several structural styles, such as high heterogeneity, water-intrusion boundary, high content of gas impurities, etc. Secondly, CO_2-EGR can result in a mixture of natural gas and CO_2 underground, which increases the cost of natural gas separation. Thirdly, the timing for CO_2-EGR is not good for its deployment, as there are not many depleted natural gas fields in China at the present. These technical difficulties and timing problems are the main barriers to large-scale deployment of CO_2-EGR projects in China. However, CO_2-EGR technology is already in existence in the natural gas production industry; therefore, the score for technical difficulties in Table 3 is chosen to be 2.

Regulation environment CO_2-EGR project can only be deployed under the framework of the current mineral resource law and environment protection law. The existing legislation and regulation framework are not sufficient for large-scale deployment of CO_2-EGR projects. Gaps exist in many aspects, such as HSE (Health, Safety and Environment), long-term liability, MVA (Monitoring, Validation and Assessment), etc.

Economy The economy of CO_2-EGR is not cost-effective without a long-term incentive policy for the current EGR technologies, due to the limited recovery of natural gas and the high cost of gas separation. Therefore, the economic aspect of CO_2-EGR in Table 3 is ranked 2.

Security CO_2-EGR does not change the reservoir properties dramatically, and natural gas reservoirs are naturally proven as effective and safe gas storage sites. The risks related to CO_2 leakage are comparable to those of CO_2-EOR, so the score in Table 3 is 3.

4.3.5 *CO_2-ESG*

Technical difficulty China has massive shale gas reserves with unique geological conditions. The old age marine shale with high maturity and new age continental shale with low maturity are both in existence [46]. Conventional extraction of shale gas, however, is constrained by a number of factors such as the tectonic stress field of deep marine that exists in complex shale due to the experience of several tectonic movements, the brittle mineral content of the continental shale is low, fracturing technology is not mature, and water resources in some basins are very limited. Even though the CO_2-ESG method has been adopted, increasing permeability by fracturing is still needed as a result of the extremely low permeability of shale. Compared to a fracture in a single-well extraction, the main fracture between injection and production wells must be avoided, which makes fracturing in CO_2-ESG different. In addition, whether or not there is a change in shale permeability may also be the key to CO_2-ESG. In short, CO_2-ESG still has no distinct and clear technical ideas regarding permeability enhancement and research on some fundamental questions, such as the change in physical properties of shale during adsorption, and desorption processes is insufficient. Therefore, CO_2-ESG scores 1 point for technical difficulty.

Regulation Environment Developing CO_2-ESG does not violate the laws of mineral resource and environmental protection. Moreover, the National Plan for the development of shale gas (2011–2015) claims an increasing effort will be made on the R&D of shale gas exploration and extraction and the implementation of encouraging policies for the shale gas industry.

Furthermore, supercritical CO_2 can be used as a medium for rock breaking and fracturing, which will share CO_2 source, transportation and storage with CO_2-ESG which is more conducive to conserving water resources and protecting the environment [31, 53, 59]. It can be said that

Table 4 Prospects of CGUS technologies in China

Technology	Tech. maturity	Tech. difficulty	Theoretical emission reduction capacity	Regulatory environment	Economy	Security	Early opportunity (%)	Long-term contribution (%)
EOR	2	3	3	2	3	3	65.0	75.0
ECBM	1	2	3	3	2	4	60.0	75.0
EGS	1	1	4	1	2	3	40.0	75.0
EGR	1	2	3	2	2	3	50.0	66.7
ESG	1	1	3	2	2	4	50.0	75.0
CMU	1	1	4	2	3	3	50.0	83.3

CO_2-ESG has a good legal and policy environment. However, as one of the CO_2 utilization methods in a fledging period, CO_2-ESG lacks support of corresponding standards and codes. As a result, CO_2-ESG takes 2 points in the regulatory environment.

Economy The shale gas production can be augmented in the case of technological breakthroughs of CO_2-ESG. Nevertheless, the capture and transportation of CO_2, drilling, operation management of injection well, etc., will increase the cost significantly. Therefore, it may not make more profits than the conventional method without encouraging policies or income from the trade in carbon and gains 2 points according to Table 3.

Security In the process of CO_2-ESG, no hazardous substance except CO_2 is involved; and CO_2, which is sequestered in adsorbed gas form, is difficult to flow. This guarantees long-term safety and reliability. So, 4 points are given to the safety of CO_2-ESG according to Table 3.

4.3.6 CO_2-CMU

Technical difficulty CO_2 mineralization and utilization is a new technology for CO_2 reduction, with no previous experience in sequestering CO_2 by CMU. Currently, the process of CMU is confronted with the problems of the high cost of material pretreatment and high investment of equipment which need further research. So, 1 point should be given.

Regulation environment The process of CO_2-CMU is mainly involved in transportation of CO_2, mineral mining and mineralization of CO_2. These processes should be undertaken under the law of mining and production of fertilizer which is already in existence, as there is no law especially for CO_2-CMU. Thus, 2 points should be given.

Economy CO_2-CMU could produce soluble potassium salt, a sulfur-based compound and magnesium carbonate as by-products, which have a high value and huge demands in the market. The costs of K-feldspar, gypsum and chloride magnesium are relatively low. So, even without the capital from a public or carbon market, CO_2-CMU might be beneficial if the consumption of energy could be reduced. So, 3 points should be given.

Security The processes of CO_2 transportation and mineral mining are relatively mature and safe. In the process of mineralizing CO_2, high pressure is needed in some of the reactions. Reactions in high pressure ranges are very common in chemical engineering, so the technology is mature and the safety risk is low. Moreover, although ammonia, a harmful gas, will be used when gypsum is the material and it would be quite dangerous if ammonia escapes, this gas is also commonly used in chemical engineering, and there is a wealth of experience of using ammonium in industry. So, three points should be given.

The prospects of CGUS technologies in China have been assessed according to the above analysis (as shown in Table 4).

According to Table 4, the early opportunity and long-term contributions of EOR are 65 and 75 %, respectively, ranking it first among all the CGUS technologies. EGS has a small early contribution, but a high long-term contribution. The long-term contribution of CMU is the highest of all the CGUS technologies. ECBM, EGR and ESG are at the intermediate level for early opportunity and long-term contribution compared with other technologies.

5 International cooperation opportunities of CGUS

Compared with developed countries such as Europe and the United States, China started late in the research and development of CGUS technology and lags behind in relevant technologies. However, in recent years, the government has put great emphasis and support on CGUS technology, especially through its cooperation with developed countries. This has enabled China to develop its CGUS technology faster and establish policies and mechanisms through international cooperation with other countries (See Table 5 for details).

China's cooperation with other countries on CGUS in recent years has greatly advanced the country's CGUS

Table 5 China's policies and mechanisms on international cooperation of CGUS

Cooperation	Main collaborator	Managerial department in China	Support areas	Annual funding	Start and end dates	Ways of cooperation	Supported projects
US-China Clean Energy Research Center	Research institutes, enterprises, universities	Ministry of Science and Technology of the People's Republic of China	CCUS	15 millions	2010–2015	Own money	(1) Large-scale post-combustion carbon dioxide capture, utilization and storage technology; (2) law and analog technologies of CO_2 geological storage and large-scale storage program
China-EU Cooperation on Near Zero Emissions Coal (NZEC)	Research institutes, enterprises, universities	Ministry of Science and Technology of the People's Republic of China	CO_2 utilization and storage in coal-fired power plants	3.5 millions £ in total	2007–2009	Funds from EU	WP4-project: CO_2 storage capacity evaluation in China
China Australia Geological Storage of CO_2	Research institutes, enterprises, universities	Ministry of Science and Technology of the People's Republic of China	CCUS	2.86 millions Australian Dollar in total	2009–2011	Funds from Australia	Research Project 1: site selection methodology and criteria for CO_2 geological storage; Research Project 2: selection criteria for oil/gas reservoirs for CO_2 EOR and geological storage; Research Project 3: studies on environmental impact and risk management of CO_2 storage
China Netherlands CO_2-ECBM and CO_2 saline aquifer storage exchange center	Research institutes, enterprises, universities		CGUS/CCS				
US-China fossil energy technology development and utilization protocol on cooperation		Ministry of Science and Technology of the People's Republic of China	CCUS		2000-now		
Energy reserves and CCUS technology International Science and Technology Cooperation Base	Research institutes, enterprises, universities	Ministry of Science and Technology of the People's Republic of China	CCUS		2011-now		
Sino-German Cooperation	Universities, research institutes	National Natural Science Foundation of China	Storage of CO_2 and energy		2010-now	Funds from Germany and China	

development and narrowed the technology gap with developed countries. On the one hand, the cooperation, including exchange of technology and talents as well as resource sharing, is beneficial to China's technology development and capacity building; on the other hand, some cooperative mechanisms bring foreign funds to China, which fill the financial gaps in the CGUS field, to some extent.

However, there is still misdirection and misconduct in some cooperative agreements, which may cause poor cooperation with no practical results. For instance, some projects do not cooperate in regard to project management, capital allocation, data sharing, achievement exchange, sharing, etc., and they fail to achieve the desired targets. In addition, many cooperation mechanisms are offering technical support only and no basic research cooperation mechanism has been established.

For an international cooperation project, it is most important to make full use of one's own advantages and make the best use of the resources from both sides, so as to achieve perfect cooperation and the expected results.

6 Conclusion and suggestion

CGUS is an economically beneficial CO_2 emission reduction technology which can enhance the development of other energies sources, besides reducing CO_2 emission. CGUS belongs to the technical category of CCUS, but is different from other CCUS technologies. This paper discusses the research status, potential and technology prospect of each CGUS technology, as well as the cooperation between China and other countries in this field. Based on the discussion, the following conclusions can be drawn:

China has been increasingly concerned about CGUS technology and is developing a variety of CGUS technologies. EOR is already in the last phase of technology demonstration and will enter the stage of industrial application soon, while other CGUS technologies are still at the stage of basic research.

The technical capacity of each CGUS technique varies from hundreds of millions of tons to billions of tons. The total capacity is huge, so it is worthwhile to invest funds in research and development. Due to limited technical knowledge, it is still difficult to evaluate the capacity for commercial application. While the commercial application capacity is generally significantly lower than the technical capacity, CGUS cannot be the major contributor to CO_2 emission reductions in China.

Among the technologies discussed in this paper, EOR possesses both a high early opportunity and a high long-term contribution, that is, 65 and 75 %, respectively; EGS has the smallest early opportunity contribution, but a high long-term contribution. The long-term contribution for CMU is the highest of all the CGUS technologies. ECBM, EGR and ESG are at the intermediate level for both early opportunity and long-term contributions compared to other technologies. This analysis may be helpful to policy makers, but since the evaluation results are possibly subjective, further research is needed for better evaluation results.

A variety of technological development cooperation mechanisms have been established in the CGUS field, but there is still a lack of a mechanism for cooperation in basic research.

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