Worldwide status of CCUS technologies and their development and challenges in China

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ABSTRACT

Carbon capture, utilization and storage (CCUS) is a gas injection technology that enables the storage of CO$_2$ underground. The CO$_2$ can be captured from a variety of stationary point sources such as power plants, cement and steel industries, and transported through pipelines or tanks to the injection locations. The aim of the CCUS technologies are twofold, on the one hand to reduce the emissions of CO$_2$ into the atmosphere and on the other hand to increase oil/gas/heat recovery. Different types of CCUS technologies and related engineering projects have a long history of research and operation in the USA. However, in China they have a short development period ca. 10 years. Unlike CO$_2$ capture and CO$_2$-EOR technologies that are already operating on a commercial scale in China, research into other CCUS technologies is still in its infancy or at the pilot-scale. This paper first reviews the status and development of the different types of CCUS technologies and related engineering projects worldwide. Then it focuses on their developments in China in the last decade. The main research projects, international cooperation, as well as pilot-scale engineering projects in China are summarized and compared. Finally, the paper examines the challenges and prospects to be experienced through the industrialization of CCUS engineering projects in China. It can be concluded that the CCUS technologies have still large potential in China. It can only be unlocked by overcoming the technical and social challenges.

**Keywords:** CCUS; oil and gas reservoirs; coal seams; shale gas; geothermal energy
Nomenclature
ACCA21: Administrative Center for China’s Agenda 21;
ADB: Asian Development Bank;
CAS: Chinese Academy of Sciences;
CCERC: China-U.S. Clean Energy Research Center;
CCS: Carbon capture, sequestration or storage;
CCTV: China Central Television;
CFHEG: Center for Hydrogeology and Environmental Geology of Chinese Geological Survey
CCUS: Carbon capture, sequestration and utilization;
CLEAN: CO₂ Large-scale Enhanced Gas Recovery project in the Altmark Natural Gas Field;
CNOOC: China National Offshore Oil Corporation;
CNPC: China National Petroleum Corporation;
CO₂-AGES: CO₂ aided geothermal extraction system;
CO₂-ECBM: CO₂ enhanced coalbed methane recovery;
CO₂-EGR: CO₂ enhanced gas recovery;
CO₂-EOR: CO₂ enhanced oil recovery;
CO₂-ESG: CO₂ enhanced shale gas recovery;
CRS: Chromium Reducible Sulfur recovery technology;
CSLF: The Carbon Sequestration Leadership Forum;
CUCMC: China United Coalbed Methane Corporation, Ltd
DFZ: Deutsche Friesenpferdezüchter;
DEFRA: UK Department for Environment, Food and Rural Affairs;
FCC: Fume from Catalytic Cracking;
GCCSI: Global Carbon Capture and Storage Institute;
GDP: Gross Domestic Product;
IEO: Intergovernmental Panel on Climate Change;
K12B: K12B gas field located at the North Sea;
1 Introduction

Fossil fuels, especially coal that is rich in carbon, constitute the highest proportion of primary energy in China [1]. In the recent years, the rapid urbanization and development of industries including power plants, cement factories, steel plants, biotransformation and fossil fuel transformation plants, which are highly dependent on large consumption of fossil fuels, has been a great challenge to the Chinese environment [2-3]. Since the winter of 2012/2013, most cities in China have been faced with serious atmospheric pollution from a haze formed from a combination of SO$_2$, NOx, inhalable particles within the mist, containing fine particle concentrations of up to ca. 900 μg/m$^3$ [4]. Automobile exhausts, industrial emissions, waste incineration and fugitive dust from construction sites are the main sources of the haze. Based on statistical data from Beijing, reported by China Central Television (CCTV) in 2014, haze particles from automobile exhausts contributed 22.2%, while the burning of coal, dust and industrial emissions accounted for proportions of 16.7%, 16.3% and 15.7%, respectively. Therefore, a reduction in the emissions from coal and industry has become the key to improving the quality of the environment.

The increase in the concentration of greenhouse gases has had a large impact on global climate change, since industrialization. Many countries have set targets for reducing the emissions of greenhouse gases in order to mitigate global warming. Among them, top on the list of CO$_2$ emissions in the world, China aims at reducing 40%−45% of its CO$_2$ emissions per unit GDP by 2020, based on the 2005 level [5-7]. This requires not only considerable changes in the framework of fossil fuel consumption, but also in the development of renewable energy from wind, solar, geothermal, etc., together with an
enlargement in the area covered by forests and innovations in technologies that can enable permanent storage of the CO₂ underground.

CO₂ emissions in China come mainly from the combustion of fossil fuels (90%) and during the process of cement manufacturing (10%). For example, in 2012, 68% of the emitted CO₂ was sourced mainly from the combustion of coal, while 13% came from oil and 7% from natural gas [8]. According to the statistics, annual emissions of CO₂ from large stationary point sources, i.e. > 0.1 Mt/year, amount to 3.89 GtCO₂, which accounts for 67% of the total emissions. Among which, 72% is from power stations [9]. This demonstrates that a reduction of the CO₂ emissions from the large stationary point sources is the key to realizing China’s target [10-11].

China’s main target for the transformation in its energy framework is to reduce the combustion of coal, while increasing the supply of natural gas and other clean energy, and controlling the emissions of CO₂, SO₂, NOx, etc. CO₂ capture and sequestration (CCS) and utilization (CCUS) technologies can be applied to store CO₂ underground effectively, thus reducing its emission into the atmosphere. This technology is now highly developed and is likely to play a significant role in China, especially when the operation costs are reduced. This paper reviews the state of the art of CCS and CCUS technologies worldwide while paying more attention on its status and development in China. The mature technology will be examined in various engineering projects. Therefore, this paper considers the state of operation of CCS and CCUS projects in detail and concludes by presenting the likely challenges to be experienced through the industrialization of these projects in China. Due to space limitation, it has not been possible to include a review of the current research status on the conversion of CO₂ to produce some commercial products or its use in the food industry, e.g. as an additive in beverages or as a preservative for fruits and vegetables. Henceforth, only its utilization for geologic and geoengineering purposes such as EOR, ECBM, ESG and EGR has been considered in this paper.

2 Worldwide development of CCS and CCUS

The CCS technology is a means to control emissions of CO₂ that are captured from different processes including pre-combustion, post-combustion, oxy-fuel combustion, etc.
The stages of a CCS project can be divided into 1) CO$_2$ capture 2) CO$_2$ transportation 3) CO$_2$ injection and 4) post-injection of CO$_2$ [12-19].

In the short term, depending on the purpose of the CCS project, CO$_2$ can be stored in different geological sites, including deep saline formations, depleted oil or gas reservoirs, deep unminerable coal seams and shale formations, to reduce the CO$_2$ emissions [20-21], Fig. 1. In comparison with the pure CCS technology, CCUS technology pays more attention to utilization (U) of the captured CO$_2$ while sequestration (S) plays a secondary role. CCUS can reduce the cost of sequestration and bring benefits by enhancing the production of hydrocarbons or heat energy, thus becoming very popular in recent years.

Based on the purpose of the CO$_2$ injection, a number of related technologies have been developed including 1) Enhanced Oil Recovery (EOR) 2) Enhanced Coalbed Methane Recovery (ECBM) 3) Enhanced Gas Recovery (EGR) 4) Enhanced Shale Gas Recovery (ESG) and 5) Enhanced Geothermal System (EGS).
Fig. 1 Schematic diagram of the CCUS technology in different geological reservoirs for both long and short-term sequestration of CO₂

The engineering projects for both CCS and CCUS technologies are systematically complicated, with their success depending on rigorous research in engineering and science disciplines including geology, geo-engineering, geophysics, environmental engineering, mathematics, computer sciences, etc. In addition, key to success in site selection for any such a project demands strict considerations of safety, economy, environment and public acceptance at all levels of operation, i.e. countrywide, basin-wide, regional or sub-basin levels [22-26], Fig. 2. Although CCS and CCUS technologies share similarities in site selection, each will induce a series of different physical and chemical responses in the underground porous or fractured rock formations, in terms of the existing local hydrological (H), thermal (T), mechanical (M) and chemical (C) fields [27-29], Fig. 2. Coupling of the THMC processes during and after CO₂ injection related with CCS and
CCUS technologies has become a research hotspot in recent years [26, 30-33]. The two technologies, however, have minor differences, in terms of purpose, storage duration, injection depth and rate, fluid and reservoir types, scheme of drilling, completion and monitoring, etc.

Fig. 2. Schematics of the two main topics, i.e. the site selection system (1) and the THMC responses (2) associated with CCS and CCUS technologies

1) CCS

CCS is a viable option for significantly reducing CO₂ emissions from large-scale emission sources. When its only purpose is for CO₂ sequestration, the storage sites may include deep saline formations, deep unminerable coal seam, depleted oil or gas reservoir and rock salt caverns [34-37]. This technology is mature but still very expensive for widespread commercial application.

2) CCUS: CO₂—EOR

The first CO₂-EOR field test was held in 1964 in Mead Strawn Texas, in the USA. Since the 1970s, CO₂ has been used on a commercial scale for oil production projects [20-21]. Up to the present time, there have been more than 100 CO₂-EOR projects in operation. Among them, the CO₂-EOR project in Weyburn, Canada is the most
successful example. It uses mixed gases separated from natural gas production, coal gasification and coal power from the Great Plains Synfuels Plant near Beulah, North Dakota USA [38]. The injection gas is mainly composed of CO$_2$ (96.8%), plus H$_2$S (1.1%) and a minor amount of hydrocarbons that are piped to the Weyburn Basin through a pipeline 339 km in length [7]. The purpose of the project is to inject 2 million tons of CO$_2$ into the depleting oil reservoir over a 20-year period, in order to increase oil recovery to 130 million barrels and to extend the production of oil in this oilfield to 25 years [39].

3) CCUS: CO$_2$—ECBM

The conventional method to produce coalbed methane is to decrease the pressure in the coalbed reservoir, making the methane desorb from the matrix. However, the recovery of coalbed methane production using this method is less than 50%. The alternative is to desorb more CH$_4$ from the coalbed matrix by injecting gases including CO$_2$ or N$_2$ [40-43]. Studies on enhancing coalbed methane by CO$_2$ injection started in the 1990s [7, 44]. When CO$_2$ is injected in the coalbed layer, both the gaseous and adsorbed-state of CH$_4$ and CO$_2$ will exist in equilibrium [45]. Because the coalbed has a much stronger adsorption capacity for CO$_2$ than CH$_4$, the injection of CO$_2$ will make the adsorbed CH$_4$ desorb, thus enhancing the CH$_4$ recovery. A proportion of the injected CO$_2$ will be stored in the coalbed formation, making it difficult for it to leak to the surface. Therefore, this technology can bring both economic benefits and also guarantee the safe storage of CO$_2$ [46-47].

The successful injection of CO$_2$ to enhance coalbed methane recovery has been proved by many experimental and numerical studies. However, the production efficiency is strongly site-dependent, in relation to the permeability of the coalbed matrix, production history, gas transportation process, maturation of coal, geological configuration, completion scheme, hydraulic pressure etc. [41-43, 48-51]. Nevertheless, the maturity of its commercial application is still very low. Pilot-scale CO$_2$-ECBM projects so far include those in Alberta in Canada which started in 1997, the Burlington project in the San Juan Basin of the USA, the RECOPOL project that started in 2001, the Yubari project in Japan and the Qinshui Basin project in China that started in 2002 [52].

4) CCUS: CO$_2$—EGR
Studies on injecting CO\textsubscript{2} into depleted gas reservoirs to enhance gas recovery started in the 1990s [53]. Unlike the CO\textsubscript{2}-EOR technology, CO\textsubscript{2}-EGR technology is still at the pilot-scale stage. Its efficiency is highly dependent on reservoir type, temperature and pressure conditions, heterogeneity, production strategy, etc. [54-59]. For some CO\textsubscript{2}-EGR projects, the gas recovered can reach 10%, while other projects have seen less or no enhancement [60-62]. The rapid breakthrough of CO\textsubscript{2} in a production well, resulting in a high concentration of CO\textsubscript{2}, restricts the production of pure natural gas [63]. Since 1999, the USA has carried out a pilot project of CO\textsubscript{2}-EGR in Rio Vista. The Netherlands injected 60 kilotonnes of CO\textsubscript{2} into a depleted gas reservoir in the K12B project during 2004 and 2009 [7]. The CLEAN project in Germany started a CO\textsubscript{2}-EGR project in the Altmark gas fields in 2009, however, public protests have prevented CO\textsubscript{2} injection on the site [64]. Many other countries including Australia, Norway etc. are also positively developing this technology [63, 65-73].

5) CCUS: CO\textsubscript{2}–ESG

The USA has been carrying out shale gas desorption since 1821. However, limited development of the technology made this process procedurally cumbersome and substantively difficult to apply before the 21st century. In 2000, shale gas contributed only 1% of the whole natural gas supply, while by the end of 2011; this proportion had increased to 30% due to a breakthrough in horizontal drilling and horizontal multi-staged fracturing technology. The revolution of shale gas in the USA is changing the energy structure of the world [74].

Encouraged by the successful application of CO\textsubscript{2} in oil and gas recovery, its application in aiding the production of shale gas began in recent years [75-80]. There has also been progress in replacing water by supercritical CO\textsubscript{2} as the injection fluid in the fracturing technology [81-85]. However, this process is still in the very early exploration stages.

6) CCUS: CO\textsubscript{2}–EGS

The first study of EGS technology started in Fenton Hill in the USA in 1970 [86]. Since then, many other countries, including France, Germany, Austria, Italy, Japan, Australia etc., have paid attention to the development of this technology. The conventional EGS technology uses water as the injection fluid and circulation media.
Based on the research in [87], CO₂ is now regarded as a more favorable circulation fluid compared with water because of its large compressibility and expansibility. This idea has already been supported by many studies (e.g. [88-92]).

The application of CO₂ in a geothermal system is not restricted to the hot dry rock reservoirs but also includes the conventional hydrothermal reservoirs [37, 90, 93]. The injection of CO₂ can enhance the efficiency of re-injecting the hot wastewater by improving the porosity and permeability through the activated water-rock geochemical reactions [94]. Besides being the main circulation fluid, CO₂ can also be regarded as a pressurized hydraulic fluid in the reservoir. Injection of CO₂ in a hydrothermal or hot dry rock reservoir can maintain the reservoir pressure, promoting the flow rate of the in situ water towards the production well, thus enhancing the heat recovery and even the recovery of the CH₄ dissolved in the aquifer water [95-98]. [37] described this process as the CO₂-AGES (CO₂-aided geothermal extraction system) in which three stages are involved: 1) the production of hot water when CO₂ is used as the pressurized hydraulic fluid; 2) two phase fluid flow in the production well after the CO₂ breakthrough; and 3) and as a circulation fluid, when CO₂ fills the production well, which is similar to CO₂-EGS.

3 CCS and CCUS engineering projects worldwide

By the end of 2016, based on the statistics of Global Status 2016, there were 38 large-scale CCS+CCUS projects in operation or under construction and planning. Among them, 17 projects are located in North America (12 projects in the United States and 5 in Canada); 12 projects in Asia (8 in China, 2 in South Korea, 1 in Saudi Arabia and 1 in United Arab Emirates), 5 in Europe (2 in Norway, 2 in United Kingdom and 1 in the Netherlands), 3 in Australia and 1 in Brazil. Among the 15 projects that are in operation, 12 projects are related to CO₂-EOR and the other 3 projects are pure CO₂ sequestration. There are 66 pilot-scale CCS+CCUS projects of which 22 are in operation, 5 under construction, 5 at the planning stage and 34 have just been completed.

Among the 70 pilot-scale engineering CCUS projects worldwide, based on their distribution by regions or countries, 22 are located in North America, 1 in South America, 22 in Europe, 20 in Asia, 4 in Australia and 1 in South Africa, see Fig. 3 for more details.
There are still no concrete CO₂-ESG and CO₂-EGS projects anywhere in the world. Only a few countries, including the USA, Canada, China and Argentina can commercially produce shale gas. At the end of 2015, the daily shale gas output in the USA, Canada, China and Argentina had reached 37, 4.1, 0.5 and 0.07 Bcf, respectively [99-100]. Shale gas production in the USA abruptly increased after 2000, while Canada and China successfully produced shale gas for the first time in 2008 and 2012, respectively. There are now more than 100,000 shale-gas drilling wells in the USA. In China, however, only about 600 wells have been drilled in the last few years [101]. The EGS technology is still at the research and development stage. Nevertheless, there are some experimental EGS plants and pilot projects, e.g. at Fenton Hill, Coso and Desert Peak in the USA, Bad Urach, Neustadt-Glewe, Bruchsal, Landau and Uterhaching in Germany and Soultz-sous-Forets and Bouillante in France [86]. Substantially higher research, development and demonstration efforts are needed to ensure EGS technology becomes commercially viable in the near future.
4 Current status of CCS and CCUS technologies in China

Since 2005, CCS has been listed as a frontier technology in China’s mid-long term technical development program in order to realize the goal of zero emissions from fossil fuel energy [102]. Meanwhile, more attention has been paid to CCUS technology, especially CO₂-EOR and CO₂-ECBM [103-106]. Between 2006-2015, the Ministry of Science and Technology of China (MOST) funded eight National Basic Research Programs (also known as the 973 Program) and State High-Tech Development Plans (commonly known as the 863 Program). Three of these programs were related to CO₂-EOR and the others to the CO₂ capture technology, shale gas recovery and the hot dry rock systems. The National Natural Science Foundation of China (NSFC) also generously funded basic research related to CCS and CCUS.

Based on the incomplete statistics of the research projects funded by MOST and NSFC during 2005-2016 (Fig. 4, Fig. 5 and Appendix 1), the distribution of funding for different aspects of CCS and CCUS are shown as follows: 1) CCS (32 projects), of which all the 7 projects funded by the MOST were related to CO₂ capture technology. The 23 projects funded by the NSFC and 1 project funded by the Ministry of Land and Resources were concerned with CO₂ storage; 2) CCUS: CO₂-EOR (18 projects), of which 6 projects were funded by the MOST and 10 by the NSFC; 3) CCUS: CO₂-ECBM (22 projects), of which 3 projects were funded by the MOST, and 17 by the NSFC; 4) CCUS: CO₂-EGR (4 projects); 5) CCUS: CO₂-ESG (4 projects); and 6) CCUS: CO₂-EGS (7 projects).

Several international cooperation research projects were also developed, including NZEC between China and Europe, CAGS between China and Australia, CCERC between China and the USA, see Table 1 for further details.
Fig. 4 Research projects of CCS and CCUS in China during 2005-2016 based on Appendix 1

Fig. 5 Different types of CCUS research projects in China during 2006-2016 based on Appendix 1
Table 1 China’s international collaboration on CCUS projects during 2005-2016

<table>
<thead>
<tr>
<th>Name of Projects</th>
<th>Main responsible institutes in China</th>
<th>Funding sources</th>
<th>Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>China-EU Cooperation on Near Zero Emissions Coal (NZEC)</td>
<td>The Administrative Center for China’s Agenda 21 (ACCA21) etc.</td>
<td>MOST, EU, UK Environment, Food and Rural Affairs (DEFRA) 2007-2009</td>
<td>4.5 million US$</td>
</tr>
<tr>
<td>China-Australia Geological Storage of CO₂ (CAGS)</td>
<td></td>
<td>MOST, Australian Department of Resources, Energy and Tourism 2010-2018</td>
<td>&gt;4.0 million US$</td>
</tr>
<tr>
<td>China-Italy CCS project</td>
<td></td>
<td>MOST, Italian Ministry of Environment 2010-2012</td>
<td>-</td>
</tr>
<tr>
<td>China-Netherlands CO₂-ECBM and CO₂ saline aquifer storage exchange center</td>
<td>Institute of Coal Chemistry (CAS) etc.</td>
<td>Ministry of Economic Affairs 2008-</td>
<td>-</td>
</tr>
<tr>
<td>China-U.S. low emission technology of IGCC</td>
<td>Institute of Engineering Thermophysics (CAS) etc.</td>
<td>MOST, U.S. DOE 2010-2012</td>
<td>-</td>
</tr>
<tr>
<td>China-U.S. Clean Energy Research Center (CCERC)</td>
<td>Huazhong University of Science and Technology</td>
<td>MOST, U.S. DOE 2010-2015</td>
<td>2 million US$/year</td>
</tr>
<tr>
<td>China-Germany CCUS project</td>
<td>Sichuan University etc.</td>
<td>NSFC, DFZ 2010-now</td>
<td>-</td>
</tr>
</tbody>
</table>

1) CCS

China’s Geological Survey compiled a series of atlases relating to the storage capacity and suitability evaluation of China and its main sedimentary basins [25, 107-111]. Combined with a selection indicator evaluation system for potential storage sites, the standardization of the CCS in China has a good foundation [20-21, 112-113]. A preliminary evaluation of the CO₂ storage potential in the saline formations at a depth of 1-3 km showed a capacity of 1.435×10¹¹ tonnes, and most parts of the Huabei plain and Sichuan Basin can be regarded as favorable storage sites [114-115]. Based on the studies on CO₂ sequestration in saline formations [116-123], the first full chain CCS project in China was successfully launched in the Ordos Basin with a storage target of 0.1 million tons of CO₂ injected in 2010 [124-129].

2) CCUS: CO₂—EOR in China
The theoretical CO\(_2\) storage capacity of depleted onshore oil reservoirs is estimated to be 3.78 gigatons of CO\(_2\) [130]. Conservative estimates reveal that about 70\% of the oil production comes from nine oilfields, i.e. Changqing, Tarim, Daqing, Shengli, Yanchang, Bohai, Liaohe, Zhongyuan and Jilin. However, most of them are facing or will soon be depleted after many years’ production. Under these circumstances, CO\(_2\)-EOR technology may become an effective option to produce more oil from the depleting reservoir. In fact, China started the development of CO\(_2\)-EOR technology in the 1960s in several districts of the Daqing oilfield including Ta #112, Fang #48, and Shu #16 and #101 [131]. Several CO\(_2\)-EOR field tests have also been carried out in other fields including Jilin, Dagang, Shengli and Liaohe (see Fig. 6), with recovery increasing to about 10\% [117, 120, 131-136]. Compared with the status of CO\(_2\)-EOR technology in the US, extensive application of CO\(_2\)-EOR in most oilfields of China may be difficult as the geologic structure of most reservoirs is characterized by many faults and low permeability [137]. Besides, a lack of policy and regulatory incentives, high commercial uncertainty and technical challenges affect the rapid development of the CO\(_2\)-EOR technology in China.

3) **CCUS: CO\(_2\)–ECBM in China**

While studies on CO\(_2\)–ECBM technology first started in the 1990s, China began its basic research in this field (including adsorption, desorption and swelling mechanisms in the coal matrix, and the two-phase gas flow of CO\(_2\) and CH\(_4\) in different types of coal rocks) at the end of 20th century [138-144]. This research was further extended to include the CH\(_4\) displacement mechanisms by using a mixture of CO\(_2\) and N\(_2\) [40, 145-150]. Based on the well test data for coalbed methane production in China, the recovery is in the range of 8.9\%-74.5\%, with an average value of 35\%. By using CO\(_2\)-ECBM technology, the recovery can be increased to 59\% [151]. Based on the preliminary evaluation of [152], the recoverable coalbed methane can increase to 1.632×10\(^{12}\) m\(^3\) with CO\(_2\) storage amount of about 120.78×10\(^8\) tonnes for the coalbed at a depth ranging from 300-1500 m.
### Fig. 6. Development of CO₂-EOR pilot tests in several oilfields in China since the 1960s

<table>
<thead>
<tr>
<th>Oilfields</th>
<th>Type of field tests</th>
<th>Field location</th>
<th>Experimental results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO₂-EOR pilot test</td>
<td>Qiaojiawa of Jingbian and Wuqi</td>
<td>recovery 4-9%</td>
</tr>
<tr>
<td>Changqing</td>
<td>CO₂-EOR pilot test</td>
<td>Shayixia</td>
<td>109.6 kilotons increased</td>
</tr>
<tr>
<td>Zhongyuan</td>
<td>CO₂ huff-puff test</td>
<td>Wen #88-Ping #1</td>
<td>recovery 13%</td>
</tr>
<tr>
<td></td>
<td>CO₂-EOR pilot test</td>
<td>Hei #59 zone</td>
<td>water content &lt; 70%</td>
</tr>
<tr>
<td>Jilin</td>
<td>CO₂ test in heavy oil</td>
<td>Fumin #14 zone</td>
<td>200 tons/well increased</td>
</tr>
<tr>
<td>Shengli</td>
<td>CO₂ huff-puff test</td>
<td>Fumin area</td>
<td>0.5%→1.2%</td>
</tr>
<tr>
<td>Jiangsu</td>
<td>CO₂ test in heavy oil</td>
<td></td>
<td>1500 tons increased</td>
</tr>
<tr>
<td>Daqing</td>
<td>CO₂ immiscible flood test</td>
<td></td>
<td>recovery 10%</td>
</tr>
<tr>
<td></td>
<td>CO₂ pilot test</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4) **CCUS: CO₂—EGR in China**

According to the results from the third oil and gas reserve investigation, if 75% of the porous volume derived from gas production is used for CO₂ sequestration, there will be a potential for a CO₂ storage capacity of 5.18 billion-tons [9, 153]. However, the gas industry in China started late and gas production is low, which means that there will not be many depleted gas reservoirs in the short term, limiting the possibility of a commercial scale application of the CO₂-EGR technology. From the maturity point of view of this technology, very few research institutes in China are working on the improvement of CO₂-EGR at the present. Furthermore, the early breakthrough of CO₂ in gas production wells makes it difficult to attain good production efficiency from the application of CO₂-EGR technology [46]. A means of reducing the costs of separating the mixed gases,
CO\textsubscript{2} and CH\textsubscript{4} is required to attain the widespread application of the CO\textsubscript{2}-EGR technology in China.

5) **CCUS: CO\textsubscript{2}—ESG in China**

Encouraged by the successful exploitation of shale gas in North America, China joined the exploration of shale gas in 2005 [154]. The published data from the Ministry of Land and Resources in 2002 confirms that China had a shale gas reserve of 25.1×10\textsuperscript{12} m\textsuperscript{3}. By the end of 2015, China had a technical shale gas reserve of about 1.3×10\textsuperscript{11} m\textsuperscript{3} including the increased proved technical reserve of 1.09×10\textsuperscript{11} m\textsuperscript{3}.

In December 2010, China drilled its first shale gas exploration well – Wei201 in Weiyuan gas field [154]. In May 2012, the first shale gas horizontal well in China was drilled and operated by Yangchang oilfield, demonstrating a great breakthrough in the hydraulic fracturing technology for shale gas reservoirs. By the end of 2012, China’s total shale gas production was 2.5×10\textsuperscript{7} m\textsuperscript{3}, which increased to 2.0×10\textsuperscript{8} m\textsuperscript{3} in 2013, 1.3×10\textsuperscript{9} m\textsuperscript{3} in 2014 and 4.47×10\textsuperscript{9} m\textsuperscript{3} in 2015. The production of shale gas in China has increased greatly during the last few years, especially from the Peiling shale gas field in Chongqing with a proved reserve of more than 1.0×10\textsuperscript{11} m\textsuperscript{3}. It has produced shale gas of about 1.03×10\textsuperscript{9} m\textsuperscript{3}, becoming the largest commercial shale gas field in China.

However, high production costs, a large amount of water consumption and a breakthrough in some key technologies related to shale gas production will restrict large scale production in the near future [101]. In 2012, the National Energy Administration of China set a target for shale gas production of 6×10\textsuperscript{10} - 1.0×10\textsuperscript{11} m\textsuperscript{3} by 2020. But after a two years’ practical experience during 2012-2013, it revised this target to 3.0×10\textsuperscript{10} m\textsuperscript{3} by 2020. Using CO\textsubscript{2} to enhance the recovery of shale gas is now at an early exploration stage [155].

6) **CCUS: CO\textsubscript{2}—EGS in China**

The 863 plan project that aims at investigating EGS was initiated by Jilin University in 2012 [156]. There are now several other projects in the country using CO\textsubscript{2} in geothermal production (see Appendix 1). This demonstrates that China is interested in developing EGS to exploit the deep geothermal resources from the hot dry rocks. Many Chinese researchers (e.g. [142, 157-161]) have already studied the operation mechanisms of the CO\textsubscript{2}-EGS system and its optimization designs. A preliminary site selection system
considering the role of CO$_2$ in the geothermal production was set up by [26]. Research in this technology is still at the very early stage and requires detailed work to attain pilot scheme status.

5 Status of CCUS engineering projects in China

The CO$_2$ emission sources are mainly located in the middle-eastern regions of China, see details in Fig. 2.15, [162]. Therefore, pilot-scale CCUS (mostly CO$_2$-EOR) engineering projects in China are also located in these regions (Fig. 5, Table 2). Based on published government and industrial reports and personal communications, the progress of pilot-scale CCUS engineering projects in China is as follows:

1) A CO$_2$-EOR field test was executed for the first time in Daqing oilfield in 2003. In recent years, the industrial injection of CO$_2$ and the production of oil with the help of CO$_2$-EOR technology operated by the Daqing oilfield is mainly located in the Yushulin and Hailaer oilfields.

2) A CO$_2$-EOR project with a CO$_2$ injection amount of 0.8-1 million tons/year in Jilin oilfield (still in operation) since 2005, exploiting the CO$_2$-rich (21% CO$_2$ concentration) Changling gasfield. A CO$_2$-EOR experiment has been carried out by Jilin oilfield in 2006 and oil recovery enhanced by 8%-10%. The Changling gas field was the first project to integrate natural gas production, CO$_2$ sequestration and EOR technology [7]. As the conventional water injection method does not provide good production efficiency in low permeable oilfields, CO$_2$-EOR has played a large role in increasing production, such as in the Fuyang oilfield [136]. By March 2017, oil production increased to 100 kilotons by injecting 1.1 million tons of CO$_2$ underground.

3) A full chain pilot-scale CO$_2$-EOR project has been injecting CO$_2$ at a rate of 40,000 tons/year in the Shengli oilfield (still in operation). The Sinopec Shengli oilfield cooperated with the Shengli power plant to install the largest equipment for capturing exhaust gases in a coal power plant [163]. Its purpose is to reduce CO$_2$ emission by 30 kilotons/year and enhance oil recovery by 20.5%. This project started in 2008 and about 251 kilotons of CO$_2$ had already been injected in the ultra-low permeable oil reservoir through 11 injection wells by April 2015.
4) A CO₂-EOR project operated by Zhongyuan oilfield (still in operation) injected CO₂ at a rate of 30,000 tons/year and managed to increase oil production by 3600 tons after injection of 2170 kilotons of CO₂ and 827 kilotons of water [7]. By February 2017, a total amount of about 553 kilotons of CO₂ was injected underground. As a result, oil recovery is proved to have enhanced by 10% in the Zhongyuan oilfield and by 60% in the Shayixia oilfield after the pilot-scale test.

5) The CO₂-EOR project led by the Yangchang oilfield company was carried out in 2013 using captured CO₂ during the production of methanol and acetic acid. At present, the capture equipment designed for 360 kilotons/year of CO₂ is under construction. Pilot-scale CO₂-EOR field tests have been done in some districts of Jinbian and Wuqi, with a total of 90 kilotons CO₂ injected.

6) As the first demonstration IGCC power station in China, the first stage of the IGCC project at Tianjin combined with the CO₂ capture and EOR technology, with an installation capacity of 265 MW, has been in operation since November 2016.

7) The CO₂-ECBM project located in the Qinshui basin of Shanxi Province operated by China United Coalbed Methane Corporation, Ltd (completed) [7, 164]. It is the only pilot scale CO₂-ECBM field test in China and operates at an injection rate of 40 tonnes/day of CO₂. This is a cooperation project between the Zhonglian coalbed methane Ltd and Canada which aims at studying the feasibility of CO₂-ECBM in China [52].

8) The full chain CCS project in the saline formations located in the Ordos of in the Inner Mongolia (completed). This is the first full chain CCS project in China, with a capital investment of more than 28.6 million US$. The drilling of one injection (with a completion depth of 2826 m) and two monitoring wells (31 and 70 m away from the injection well) started in 2010. Since September 2011 until 2015, a total amount of 300,000 tons CO₂, produced by the coal liquefaction factory of the Shenhua Group, has been transported by oil tankers and injected in four saline formations and one carbonate formation [165]. The first stage of injection test started in 2011, with the wellhead injection pressure...
ranging from 6.79 - 8.63 MPa. The second production test started in 2012 with varying injection rates of 6 m$^3$/h, 9 m$^3$/h, 12 m$^3$/h and 15 m$^3$/h and constant wellhead injection pressure of 5.7 MPa and temperature of 5 °C. Another large-scale CO$_2$ sequestration in the deep saline formations located in Lianyungang of Jiangsu Province is in preparation. Another large-scale CO$_2$ sequestration in the deep saline formations located in Lianyungang of Jiangsu Province is in preparation.

9) A CO$_2$ storage project in the rock salt at Yingcheng in Hubei Province, where CO$_2$ will be captured by the oxy-fuel combustion technology, is in preparation [166];

10) CO$_2$ sequestration by microbe algae has also been identified an effective means to reduce CO$_2$ concentration in the atmosphere. The two representative CO$_2$ sequestration projects using microbe algae are the Xin’ao and Qinghua groups both from China.

In the next few years, CO$_2$-EOR engineering projects will still be the most important CCUS technology in application. After the successful experience attained from the pilot-scale CCUS projects so far, China is now planning to run 13 large-scale CCUS projects. Based on the stages of the engineering projects, the project will be divided into the following study phases: opportunity $\rightarrow$ preliminary $\rightarrow$ pre-feasibility $\rightarrow$ feasibility $\rightarrow$ construction drawing design $\rightarrow$ construction $\rightarrow$ operation $\rightarrow$ completed. All the stages before the construction drawing design phase, i.e. preparation of the engineering projects, could be lumped together and called the “evaluation” stage. Due to the current low oil price and a lack of the motivation policy, the progress in developing most of these large-scale planning CCUS projects lags far behind the schedule. Most of these projects are still at pre-feasibility or feasibility stages and some may even be cancelled.

Although capturing and industrial utilization of CO$_2$ in China are not the key aims of this paper, the related projects in operation include: 1) Huaneng Beijing thermal power plant; 2) Huaneng Shanghai Shidongkou; 3) China Power Investment Corporation Chongqing Shuanghuai; 4) CO$_2$ project in Hainan operated by China National Offshore Oil Corporation (CNOOC); 5) CO$_2$ project in Jiangsu province operated by the Zhongke CO$_2$ Jinlong company. The CO$_2$ pilot scale project in Tianjin organized by China Guodian Power is in preparation.

At the present, China does not execute any CO$_2$-EGS field test. However, a few
engineering EGS projects exist at their early scientific field test stages. These include: 1) the hot dry rock scientific drilling project in Zhangzhou Fujian province, in operation since May of 2015, with a drilling depth of 4000 m and a water temperature high enough for geothermal power generation and 2) a hot dry rock scientific drilling project in Qinghai Province, with a water temperature of 200 °C at a depth of 3000 m [156]. Studies on power generation in traditional hydrothermal fields located in Yangyi, Xizang and Tengchong in Yunnan Province are also undergoing. However, there are no active engineering projects related with CO₂-EGR and CO₂-ESG in China.

**Fig. 7** Distribution of CCUS engineering projects in China excluding the South China Sea Islands (numbers defined in Table 2) superimposed on the provincial CO₂ emission map for the year 2010 (from [162])
<table>
<thead>
<tr>
<th>Projects</th>
<th>Location</th>
<th>Scale tons/yr</th>
<th>CO₂ capture method</th>
<th>Storage/Utilization</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. CO₂-EOR project by Daqing oilfields</td>
<td>Yushulin, Hailaer</td>
<td>—</td>
<td>—</td>
<td>EOR</td>
<td>Operation</td>
</tr>
<tr>
<td>2. CO₂-EOR project by Jilin oilfield</td>
<td>Songyuan</td>
<td>0.28 million</td>
<td>Liquefaction of FCC flue gas</td>
<td>EOR</td>
<td>Operation</td>
</tr>
<tr>
<td>2-1. Second stage of EOR project in Jilin oilfield</td>
<td>Songyuan</td>
<td>Planned for 0.5 million</td>
<td>Pre-combustion from the separation of natural gas production</td>
<td>EOR</td>
<td>Operation</td>
</tr>
<tr>
<td>3. CO₂-EOR project by Shengli oilfield</td>
<td>Dongying</td>
<td>40,000</td>
<td>Post-combustion</td>
<td>EOR</td>
<td>Operation</td>
</tr>
<tr>
<td>4. EOR project by Zhongyuan oilfield</td>
<td>Puyang</td>
<td>100,000</td>
<td>Post-combustion</td>
<td>EOR</td>
<td>Operation</td>
</tr>
<tr>
<td>5. EOR project by Yanchang oilfield</td>
<td>Yanchang</td>
<td>400,000</td>
<td>Coal liquefaction plant</td>
<td>EOR</td>
<td>Operation</td>
</tr>
<tr>
<td>6. First stage of Huaneng greengen IGCC in Tianjin</td>
<td>Tianjin</td>
<td>—</td>
<td>Pre-combustion</td>
<td>Planned for EOR</td>
<td>Operation</td>
</tr>
<tr>
<td>7. CO₂-ECBM by China United Coalbed Methane Ltd.</td>
<td>Jincheng</td>
<td>40 /day</td>
<td>Purchase of CO₂</td>
<td>ECBM</td>
<td>Completed</td>
</tr>
<tr>
<td>8. Full chain CCS project by Shenhua Group</td>
<td>Ordos</td>
<td>100,000</td>
<td>Coal liquefaction plant</td>
<td>Saline formation</td>
<td>Completed</td>
</tr>
<tr>
<td>9. Pilot project of IGCC clean energy in Lianyungan</td>
<td>Lianyungan</td>
<td>1000,000</td>
<td>Pre-combustion</td>
<td>Planned in saline formation</td>
<td>Preparation</td>
</tr>
<tr>
<td>10. 35 MWt oxy-fuel combustion in Zhongyan Yingcheng of Hubei</td>
<td>Yingcheng</td>
<td>100,000</td>
<td>Oxy-fuel combustion</td>
<td>Sequestration in the salt rock</td>
<td>Preparation</td>
</tr>
<tr>
<td>11. CO₂ capture and storage pilot project by China Resources Power</td>
<td>Dongguan</td>
<td>1 million</td>
<td>Pre-/post-combustion from power station and oil refinery</td>
<td>Planned for EOR or saline formation</td>
<td>Pre-feasibility study</td>
</tr>
<tr>
<td>12. Coal-to-liquids project in Ningxia by Shenhua Group</td>
<td>Ningxia</td>
<td>2 million</td>
<td>Pre-combustion from the coal-to-liquids process</td>
<td>Undefined</td>
<td>Opportunity study</td>
</tr>
<tr>
<td>13. Third stage of Huaneng greengen IGCC in Tianjin</td>
<td>Tianjin</td>
<td>2 million</td>
<td>Pre-combustion from the power station</td>
<td>Planned for EOR saline formation</td>
<td>Not start</td>
</tr>
<tr>
<td>14. Second stage of coal-to-liquids project by Shenhua Group</td>
<td>Ordos</td>
<td>1 million</td>
<td>Pre-combustion from the coal-to-liquids process</td>
<td>Saline formation</td>
<td>Pre-feasibility study</td>
</tr>
<tr>
<td>15. CCS project by Sinopec Qilu Petrochemical</td>
<td>Dongying</td>
<td>0.5 million</td>
<td>Pre-combustion from oil refinery</td>
<td>EOR</td>
<td>Preliminary design</td>
</tr>
<tr>
<td>Project Description</td>
<td>Location</td>
<td>Cost</td>
<td>Combustion Type</td>
<td>Sequestration</td>
<td>Status</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------------------</td>
<td>-------------</td>
<td>---------</td>
<td>----------------------------------------------------------</td>
<td>---------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>16. CCS project of Shengli power station by Datang Group</td>
<td>Dongying</td>
<td>1 million</td>
<td>Post-combustion from the power station</td>
<td>EOR</td>
<td>Pre-feasibility study</td>
</tr>
<tr>
<td>17. CO₂ capture and EOR in coal chemical industry by Yangchang Petroleum Co. Ltd.</td>
<td>Yanchang</td>
<td>5,0000</td>
<td>Pre-combustion from coal chemical industry</td>
<td>EOR</td>
<td>Operation</td>
</tr>
<tr>
<td>17-1. Second stage of CO₂ capture and storage project by Yanchang Group</td>
<td>Yanchang</td>
<td>1 million</td>
<td>Pre-combustion from coal chemical industry</td>
<td>EOR</td>
<td>Not start</td>
</tr>
<tr>
<td>18. CO₂ capture and storage pilot project in Daqing oilfield by Datang Group</td>
<td>Daqing</td>
<td>1 million</td>
<td>Oxy-fuel combustion from the power station</td>
<td>Planed for EOR + saline formation</td>
<td>Pre-feasibility study</td>
</tr>
<tr>
<td>Coal-to-gas project by CNOOC</td>
<td>Datong</td>
<td>1 million</td>
<td>Pre-combustion from coal-to-gas process</td>
<td>Planed for EOR + saline formation</td>
<td>Pre-feasibility study</td>
</tr>
<tr>
<td>Coal-to-gas project by CNOOC Ordos*</td>
<td>Ordos</td>
<td>1 million</td>
<td>Pre-combustion from coal-to-gas process</td>
<td>Planed for EOR + saline formation</td>
<td>Pre-feasibility study</td>
</tr>
<tr>
<td>Coal-to-olefin Ordos project by CPIC and TOTAL*</td>
<td>Ordos</td>
<td>1 million</td>
<td>Pre-combustion from coal-to-olefin process</td>
<td>Planed for EOR + saline formation</td>
<td>Pre-feasibility study</td>
</tr>
<tr>
<td>CCUS project by Shanxi international energy group*</td>
<td>Shanxi</td>
<td>2 million</td>
<td>Oxy-fuel combustion from the power station</td>
<td>Undefined</td>
<td>Pre-feasibility study</td>
</tr>
</tbody>
</table>

**Industrial conversion of the captured CO₂, not for underground geological sequestration**

<table>
<thead>
<tr>
<th>Project Description</th>
<th>Location</th>
<th>Cost</th>
<th>Combustion Type</th>
<th>Product</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>19. Pilot project of CO₂ sequestration by micro algae of Xin’ao Group</td>
<td>Dalate qi</td>
<td>320,000</td>
<td>Flue gas of the coal chemistry factory</td>
<td>Microbe sequestration</td>
<td>Construction</td>
</tr>
<tr>
<td>20. SNG project in Qinghua of Xinjiang</td>
<td>Yili in Xinjiang</td>
<td>–</td>
<td>Pre-combustion</td>
<td>Microbe sequestration</td>
<td>Operation</td>
</tr>
<tr>
<td>21. Geothermal power station in Gaobeidian of Beijing by Huaneng</td>
<td>Beijing</td>
<td>3000</td>
<td>Post-combustion</td>
<td>Food and industry use</td>
<td>Operation</td>
</tr>
<tr>
<td>22. Shidongkou project in Shanghai by Huaneng</td>
<td>Shanghai</td>
<td>120,000</td>
<td>Post-combustion</td>
<td>Food and industry use</td>
<td>Operation</td>
</tr>
<tr>
<td>23. Shuanghuai power plant project</td>
<td>Chongqing</td>
<td>10,000</td>
<td>Post-combustion</td>
<td>N/A</td>
<td>Operation</td>
</tr>
<tr>
<td>24. CO₂ project in Hainan</td>
<td>Dongfang</td>
<td>2100</td>
<td>Separation from natural gas</td>
<td>Biodegradable plastics</td>
<td>Operation</td>
</tr>
<tr>
<td>25. CO₂ project in Jiangsu</td>
<td>Taixing</td>
<td>8000</td>
<td>Alcohol factory</td>
<td>Chemical material</td>
<td>Operation</td>
</tr>
<tr>
<td>26. CO₂ pilot project in Tianjin</td>
<td>Tianjin</td>
<td>20,000</td>
<td>Post-combustion</td>
<td>Food</td>
<td>Preparation</td>
</tr>
</tbody>
</table>

**Note:** projects marked with * threaten cancellation in the near future for unknown reasons.
6 Challenges in the widespread application of CCUS in China

1) **Tackling problems in key technologies:** The injection of CO$_2$ underground for the CCS and CCUS purposes involves multiple physical-chemical coupling interactions of multiple components in porous fractured media, especially the transmission and migration of fluids between porous media with a low/ultra-low permeability and complex fractured network.

a. There are mature commercial CO$_2$-EOR technologies in the USA and Canada. In China, however, because of the strong heterogeneity in oil reservoirs, the CO$_2$ channeling effect is serious [137]. Therefore, improving the sweep efficiency is the key to attaining widespread application of CO$_2$-EOR in China. Other efficient methods include the alternating injection of water and CO$_2$ (WAG) and the addition of foaming and gelling agent [131].

b. There are currently no commercial scale CO$_2$-ECBM engineering projects being developed anywhere in the world. In China, studies on CO$_2$-ECBM technology are at a very early stage of exploration. More research is required to tackle key problems including the adsorption-desorption process between CH$_4$ and CO$_2$ in the coal seam [45, 145-146], the mechanisms of the interaction between CO$_2$-CH$_4$-H$_2$O at molecular scale [149], the impact of the coal grade, water content and composition of coal etc. on the diffusion and migration of mixed gases in the coal seam, the dynamic changes of phase behavior during the process of CO$_2$ injection and CH$_4$ production etc.

c. In the application of the CO$_2$-EGR technology, more effort is required to prevent the early breakthrough of CO$_2$ into the production well, thus enhancing the sweep efficiency of CO$_2$. Thus more studies are needed including the understanding of migration processes of the CO$_2$ after its injection into the depleted gas reservoir, phase behaviour, the mixing mechanism of CO$_2$ and CH$_4$, etc. [47, 59].

d. Multi-stage hydraulic fracturing in the horizontal wells has been widely used in shale gas production in China. However, this technology is still not mature enough for the production of shale gas at depths >3500 m. The large amount of water consumed in the production of shale gas is a big challenge for its large-scale production, especially in Southwestern China, where the existing water resources are very poor. Using CO$_2$ as the
fracturing fluid has become a research hot spot in China [167]. Injection of CO₂ to extract brine or methane energy from the aquifers was also studied recently [168]. While the feasibility of using CO₂ to enhance shale gas recovery still requires more research and field tests.

e. The direct use of geothermal energy in China has been the priority during the last few years, while its use for power generation largely lags behind that of several countries, such as the USA, the Philippines, Japan, and Indonesia etc. Technologies including CO₂-AGES, EGS and binary cycle power plants may have a positive effect on the development of China’s geothermal power system. However, before obtaining mature engineering experiences, China needs to enlarge its investment in human, physical and financial resources in these technologies.

2) **Negative impacts on the environment and resources:** The risk of leakage of the injected CO₂ in the injection/production wells may have a serious environmental impact [169-173]. The groundwater quality may deteriorate if the CO₂ in the injection layer leaks into the freshwater aquifer through micro fractures or faults [174-175]. When hydraulic fracturing is applied to shale gas or geothermal energy production, it will induce microseismic events. In addition, the toxic chemical additives in the hydraulic fluid may have a serious negative impact on freshwater aquifers when they leak into the shallow layers because of possible geological hazard. Therefore, a long-term environmental monitoring activity should be carried in parallel with the CCUS engineering project to ensure its safety [103]. The dynamic migration process of CO₂, chemical interaction among CO₂ -reservoir fluid-rock, the deformation or eruption of injection/overlying caprocks, temperature and pressure changes in the reservoir should be monitored for a long time after the injection [29, 176].

3) **Storage capacity data is not clear:** The total amount of resources and the distribution of depleted oil and gas fields, deep unminerable coal seams, deep saline formations, shale gas and rock salt reservoirs are not clearly known because of the inadequacy of the geological data. Thus to attain a widespread application of CCUS technologies, more accurate evaluation work should be done based on geological, geophysical, geochemical, rock mechanics data etc.

4) **Policy factor:** The positive effect of China’s involvement in CCUS technologies
in recent years has been to focus on developing CO₂-EOR, the capture of CO₂, the shale gas and hot rock geothermal energy production, and especially shale gas production with a subsidy of 4 US¢/m³ during 2016-2018 and 3 US¢/m³ during 2019-2020. However, other fields of CCUS also need to be supported by the government.

**5) High investment costs:** The cost of a CCS or CCUS project mainly includes CO₂ capture, transportation, drilling, injection and monitoring etc. Costs for the capture of CO₂ produced by the technologies of pre-combustion, post-combustion or oxy-fuel combustion take the largest proportion in the investment of a specific CCS or CCUS project. Taking a coal-fired power station as an example, if 80% of the CO₂ emitted is captured and compressed to a certain pressure, its energy consumption will increase by 24%-40% [177]. In the US, the price of electricity generated from a coal-fired power station is 82-99 US$/MWh and 83-123 US$/MWh without and with the CO₂ capture technology respectively [178]. Depending on different situations and technologies in US, the capture cost is 42-87 US$/ton CO₂, transportation costs range from 4.3-7.2 US$/ton CO₂/250 km, while injection and storage costs are 1-12 US$/ton CO₂ based on the prices in 2013. In China, the cost of electricity generation by coal-fired power station increases by 30%-50% using CO₂ capture technology due to the extra consumption of electricity and steam. Taking the Huaneng Beijing coal-fired power station as an example, the capture price is about 24.3 US$/ton CO₂, with the CO₂ capture efficiency of 80%-85% [179]. On the other hand, simulation results of the IGCC coal-fired power station with the CCS technology in Tianjin show the capture price to range from 21.3-24.8 US$/ton CO₂, accounting for 80% of the price of a full-scale CCS project [180-181]. However, the uncertainty in the CO₂ capture price is high depending on different capture technologies including pre-combustion, post-combustion and oxy-fuel combustion at various stationary point sources including coal-fired power stations, cement factories, coal chemical industries, etc. From the aforementioned point of view, the uncertainty in the investment of a specific CCS or CCUS engineering project is determined by the cost of CO₂ capture. Therefore, a reduction in the cost of CO₂ capture is the key to the widespread application of CCS or CCUS technologies. Besides, drilling costs are large for all types of CCUS engineering projects and hydrocarbon/geothermal production, taking a shale gas well as an example, it costs 5.8 million US$ for a drilling length of
2500-3000 m, and 0.72 million US$ for a general gas well. The drilling cost of a geothermal production well in a hot dry rock will be much higher. The corrosion property of CO$_2$ requires a high quality of pipelines and ground equipment, increasing the production costs of oil, gas and geothermal energy [182-183].

6) **Energy price:** The slump in the international oil price has greatly affected the investment in the oil/gas production and CCUS projects. Shale gas production in Peiling shale gas field in southwestern China with good geological conditions and large reserves is just above the breakeven point. If the oil/gas price remains low in the future, many industries will be unwilling to invest in these kinds of projects. With the exception of CO$_2$-EOR, it is difficult to profit from other CCUS projects. Due to completion from the increased installation capacity of wind and solar energy that have been much easier to make an economic return in recent years, the development in geothermal power generation will be continuously limited because of the difficulty in returning an economic benefit.

7) **Social acceptance:** This is the biggest challenge for any CCS or CCUS project. It has a substantial impact on political decision makers and the implementation of energy projects such as nuclear power and wind energy programs [184]. It is the same for CCS and CCUS projects, and some CCS exploration activities in Schleswig-Holstein and Vattenfall Janschwalde in Germany, the Belchatow project in Poland etc. were postponed or cancelled because of the lack of public acceptance over the exploration of storage sites [185-186]. As the most unfamiliar technology to the general public in China, CCUS technology has been reluctantly accepted when compared with other low carbon technologies including wind power, solar power, energy efficiency or biomass etc. for reasons of climate change mitigation [10, 187]. However, there is now a positive attitude towards CCUS policies in China. In order to stimulate public acceptance, the uncertainties regarding safety and environmental risks involved in CCUS will have to be reduced at the beginning of the development stage of any CCUS technology [188]. However, this will be largely dependent on the innovation of long-term monitoring techniques in both operating and planned pilot projects [189-190].
7 Conclusions

1) Many countries have participated in activities to tackle global climate changes during the last few years. The total CO$_2$ emissions for China in 2005 were 59.76×10$^8$ tonnes, accounting for 80.03% of the greenhouse gas emission of China in 2016. To perform its social responsibility, China plans to reduce its CO$_2$ emission per unit of GDP by 40%-45% in 2020 compared with the 2005 level. Therefore, on one hand, China needs to change its current energy framework by reducing the consumption of fossil fuels like coal energy, or applying a clean coal program, capturing the CO$_2$ produced by the combustion of coal. On the other hand, China needs to develop the renewable energy sector, including wind energy, solar energy, geothermal energy etc.

2) The serious air pollution problems in recent years are forcing the government of China to pay more attention to the development of green and clean energy aimed at saving energy and reducing the emissions of greenhouse gases. Some local governments have increased their investment in modern coal fired power station coupled with the CCS technology. The CCUS engineering projects, especially those related to EOR, are also developing fast.

3) Traditional CCS projects can store a large amount of CO$_2$, captured from large-scale point source emission sites, deep underground, thus effectively decreasing emissions in the atmosphere. CCUS is more attractive than the CCS technology in China because of the economic benefits accrued by using the CO$_2$. China has large reserves of low permeable oil and gas reservoirs. The conventional water injection methods cannot achieve good production efficiency in such reservoirs, therefore the CO$_2$-EOR and CO$_2$-EGR will have a great potential in enhancing the recovery of oil and natural gas in low and ultra-low permeable reservoirs, as well as storing CO$_2$ in the underground space. The CCUS technology will play a considerable role in controlling the reduction of CO$_2$ emissions related to coal fired power stations and the coal chemical industry. For a long period of time, coal will remain the main energy source in China, thus CCUS technology is very important for cleansing the coal-based industry. CO$_2$ has the potential to be used in the production of geothermal energy because of its favourable physical properties including large density, small viscosity etc. In addition, studies on replacing water by supercritical CO$_2$ as the fracturing fluid in the oil/gas/shale gas reservoirs are currently
being carried out by many researchers. If this method is proved to be feasible, it will greatly decrease water consumption in the production of shale gas. This is particularly meaningful in the western regions of China where there is lack of groundwater resources.

**Competing Interests**

The authors hereby declare that there is no conflict of interests regarding the publication of this paper.

**Acknowledgments**

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**References**


[77] C. Ou, Y. Zeng, “Research prospect of CO2 sealing up for safekeeping and CO2 enhanced


L. Zhou, Q. Y. Feng, X. D. Li, “Mechanism and application potential of geological sequestration of carbon dioxide in deep coal seams,” Earth and Environment, vol. 35, no. 1,


### Appendix 1

The research projects of CCUS funded by China Ministry of Science and Technology (MOST) and National Natural Science Foundation of China (NSFC) etc. during 2005-2016 (amount unit: 10,000 RMB or 1,450 US$)

<table>
<thead>
<tr>
<th>Type 1: CO₂-EOR</th>
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<td>Utilization of CO₂-EOR and geological storage of CO₂</td>
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<td>CO₂ capture and storage technologies</td>
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<td>Basic studies on the transportation of supercritical CO₂, water and oil in the low permeable porous media</td>
<td>Dalian University of Science and Technology</td>
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<td>QSAR studies on the thermodynamics and transportation properties of CO₂—EOR system</td>
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<td>Studies on the surface properties using alkylol amine capture CO₂ and processes of CO₂-EOR</td>
<td>North China Electric Power University</td>
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<td>Microscopic mechanism, quantification and optimization of injection-production scheme of CO₂-EOR and CO₂ sequestration in the oilfield</td>
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<td>Technical development of CO₂ capture from the flue gas of the large-scale coal-fired power station, EOR and storage and pilot projects</td>
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<td>CO₂—ECBM potential in China and the suitability evaluation</td>
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<td>Mechanism of using mixtures of CO₂/N₂ displace coalbed methane in situ geological conditions and the best ratio of gas composition</td>
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<td>Impacts of coal matrix on the coal expansion and permeability changes of CO₂/CH₄ during the CO₂—ECBM process</td>
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<td>Solid-gas interaction during CO₂ sequestration in the deep coal seam and simulation of the sequestration experiment</td>
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<td>Advanced models of CO₂—ECMB</td>
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<td>Adsorption and desorption mechanisms of multiple gases during CO₂—ECBM process</td>
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<td>Experimental study of coal matrix on expansion effects during CO₂—ECBM process</td>
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<td>Two-phase gas and solid coupling effect and dual porosity effect during the CO₂ sequestration in the deep coal seam</td>
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<td>Dynamic model of multiphase fluid CH₄-water flow in porous media of heterogeneous coal seam</td>
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<td>Fluid-solid coupling response and mechanism of supercritical CO₂ and minerals in the coal</td>
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<td>Interaction of supercritical CO₂ and organic matter in the coal and their responses to the coal structure</td>
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<td>The construction of 3D model of reservoir structure in the high grade coal and the geochemical response to the injection of CO₂</td>
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<td>CO₂ enhance CH₄ adsorbed by the coal, the permeability characteristics and mechanisms</td>
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<td><strong>Interaction of supercritical CO2 and coal during CO2 sequestration in the deep coal seam and its impact on the CO2 storage</strong></td>
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<td><strong>Transportation mechanisms of supercritical CO2 injection into the stress partition residual coal pillar and its displacement of CH4</strong></td>
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<td><strong>Basic research on the mechanism of CO2-ECMB in the deep low permeable unminerable coal seam under THM coupling effect</strong></td>
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<td><strong>Safety production of the CO2 bearing gas reservoir and the utilization of CO2</strong></td>
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<td><strong>Pilot project of the production of the CO2 bearing volcanic gas reservoir and utilization</strong></td>
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<td><strong>CO2 sequestration mechanism in the depleted gas reservoir and the transportation rules</strong></td>
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<td><strong>Phase behavior of supercritical CO2 displacing CH4 in the porous media and the seepage characteristics</strong></td>
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<td><strong>Simulation and prediction of CO2-EGS</strong></td>
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### Type 6: CO₂ capture technology

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<td>R&amp;D of the new type O₂/CO₂ circulated combustion equipment and the optimization of system</td>
<td>Huazhong University of Science and Technology</td>
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<td>Key technologies of CO₂ capture by using 35MWth oxy-fuel combustion technology, R&amp;D in equipment and pilot projects</td>
<td>Huaneng Group etc.</td>
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<td>R&amp;D in key technologies of CO₂—inoleaginous microalgae—biodiesel</td>
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<td>IGCC-based CO₂ capture, utilization and sequestration technologies and pilot projects</td>
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### Type 7: CO₂ storage in the saline formation (CCS technology)

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<td>Multiphase multi-component reactive transportation mechanism of sequestration of impure CO₂ and numerical simulation</td>
<td>Institute of Rock and Soil Mechanics (CAS)</td>
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<td>HMC coupling mechanism of CO₂ sequestration in the saline formations, stability of rock and the transportation rules of CO₂</td>
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<td>Geochemical studies on the supercritical CO₂-rock-saline water system</td>
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<td>Mechanisms of the water-rock-gas interaction of the CO₂ sequestration in the saline aquifers in the pressurized sedimentary basin</td>
<td>Nanjing University</td>
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<td>Dongnan University</td>
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<td>The diffusion mechanism of CO₂ in porous media and its quantitative relationship with the propagation rate of the CO₂ front</td>
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<td>Beijing University of Technology</td>
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<td>Evolution of the damage in the near-field neighboring rocks of the CO₂ storage site in the rock salt and the integrity studies</td>
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<td>Transportation rule and trapping mechanisms of CO₂ geological sequestration in the multi-scale heterogeneous saline formations</td>
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<td>Impacts of reservoir heterogeneity on the capacity of CO₂ in the saline formations</td>
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<td>Mechanisms of the difference in the distribution of the CO₂ saturation based on the high reliable saline formation model</td>
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<td>Physical property measurements on the CO₂-saline water system in the CO₂ geological sequestration</td>
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<td>Impacts of the physical properties of the porous media on the two phase (CO₂, saline water) fluid flow and the trapping mechanism of CO₂</td>
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<td>Two phase CO₂-water fluid flow characteristics and trapping mechanism of CO₂ at the porous scale in the multiple porous media</td>
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<td>The convective mixing of CO₂ sequestration in the saline formations and its development characteristics</td>
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