Hindawi
Geofluids
Volume 2017, Article ID 6126505, 25 pages
https://doi.org/10.1155/2017/6126505

WILEY | Hindawi

Review Article

Worldwide Status of CCUS Technologies and Their Development and Challenges in China

H. J. Liu,[1] P. Were,[2] Q. Li,[3] Y. Gou,[2,4] and Z. Hou[2,4,5]

[1]*INRS-ETE, Universite du Québec, Québec, QC, Canada*
[2]*Energie-Forschungszentrum Niedersachsen, Clausthal University of Technology, Goslar, Germany*
[3]*State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China*
[4]*Sino-German Energy Research Center, Sichuan University, Chengdu, China*
[5]*Institute of Petroleum Engineering, Clausthal University of Technology, Clausthal-Zellerfeld, Germany*

Correspondence should be addressed to Y. Gou; yang.gou@efzn.de and Z. Hou; hou@tu-clausthal.de

Received 19 February 2017; Revised 12 May 2017; Accepted 20 June 2017; Published 28 August 2017

Academic Editor: Weon Shik Han

Carbon capture, utilization, and storage (CCUS) is a gas injection technology that enables the storage of CO_2 underground. The aims are twofold, on 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, and 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.

1. Introduction

Fossil fuels, especially coal that is rich in carbon, constitute the highest proportion of primary energy in China [1]. In 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, have 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, and inhalable particles within the mist, containing fine particle concentrations of up to ca. 900 $\mu g/m^3$ [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 considerable changes not only in the framework of fossil fuel consumption, but also in the development of renewable energy from wind, solar, geothermal, and so on, together with an enlargement in the area covered by forests

and innovations in technologies that can enable permanent storage of the CO_2 underground.

CO_2 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 CO_2 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 CO_2 from large stationary point sources, that is, >0.1 Mt/year, amount to 3.89 $GtCO_2$, which accounts for 67% of the total emissions. Among which, 72% is from power stations [9]. This demonstrates that a reduction of the CO_2 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 CO_2, SO_2, NOx, and so on. CO_2 capture and sequestration (CCS) and utilization (CCUS) technologies can be applied to store CO_2 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 CO_2 to produce some commercial products or its use in the food industry, for example, 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 CO_2 that are captured from different processes including precombustion, postcombustion, and oxy-fuel combustion. The stages of a CCS project can be divided into (1) CO_2 capture, (2) CO_2 transportation, (3) CO_2 injection, and (4) postinjection 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 unmineable coal seams, and shale formations, to reduce the CO_2 emissions [20, 21], Figure 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).

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, geoengineering, geophysics, environmental engineering, mathematics, and computer sciences. 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, that is, countrywide, basin-wide, regional, or subbasin levels [22–26], Figure 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], Figure 2. Coupling of the THMC processes during and after CO_2 injection related to 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, and so on.

2.1. CCS. CCS is a viable option for significantly reducing CO_2 emissions from large-scale emission sources. When its only purpose is for CO_2 sequestration, the storage sites may include deep saline formations, deep unmineable coal seam, depleted oil or gas reservoir, and rock salt caverns [35–38]. This technology is mature but still very expensive for widespread commercial application.

2.2. CCUS: CO_2-EOR. The first CO_2-EOR field test was held in 1964 in Mead Strawn Texas, in the USA. Since the 1970s, CO_2 has been used on a commercial scale for oil production projects [20, 21]. Up to the present time, there have been more than 100 CO_2-EOR projects in operation. Among them, the CO_2-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 [39]. The injection gas is mainly composed of CO_2 (96.8%), plus H_2S (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 [40].

2.3. 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 [41–44]. Studies on enhancing

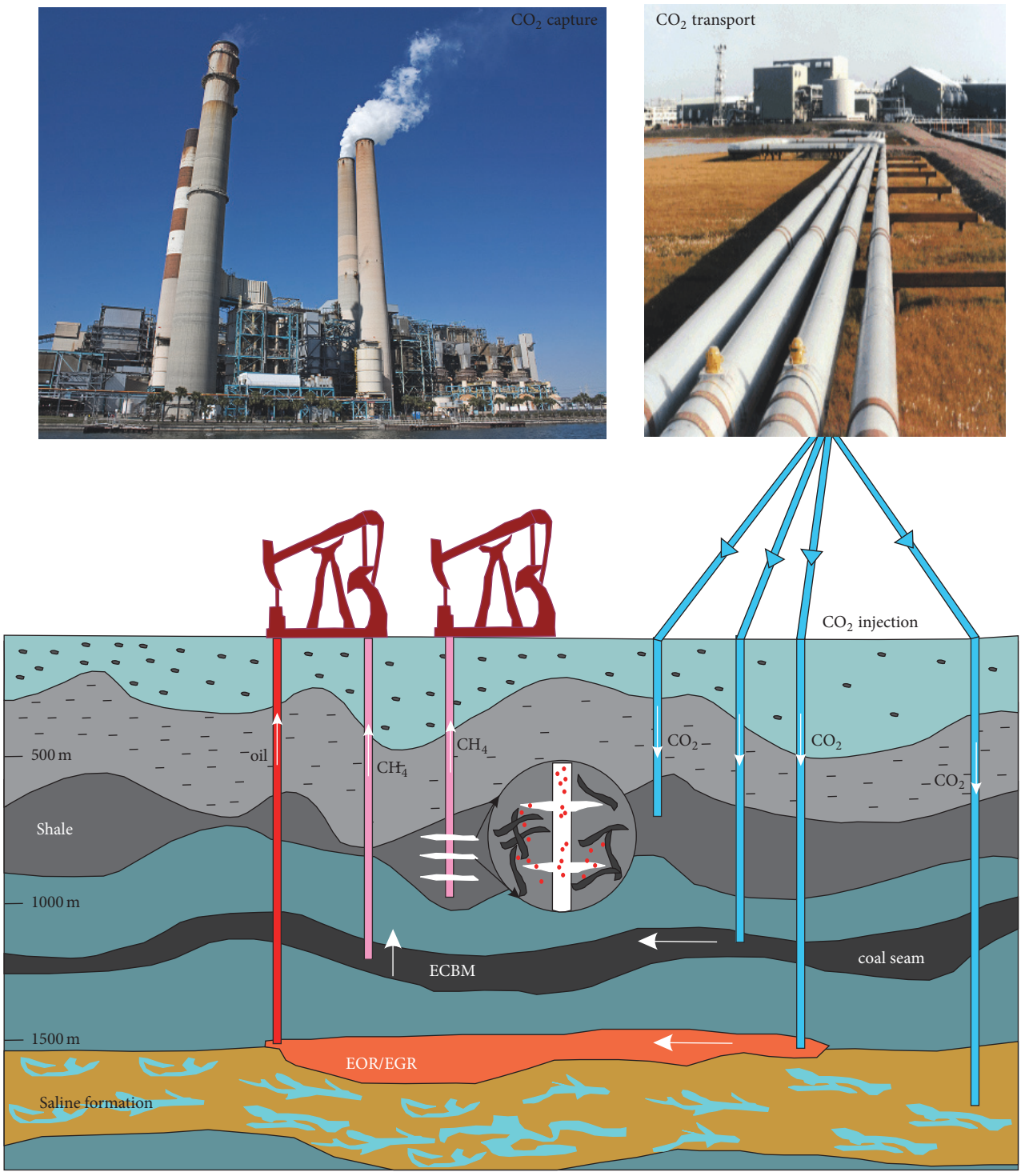

FIGURE 1: Schematic diagram of the CCUS technology in different geological reservoirs for both long and short-term sequestration of CO_2.

coalbed methane by CO_2 injection started in the 1990s [7, 45]. 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 [46]. 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 [47, 48].

The successful injection of CO_2 to enhance coalbed methane recovery has been proved by many experimental

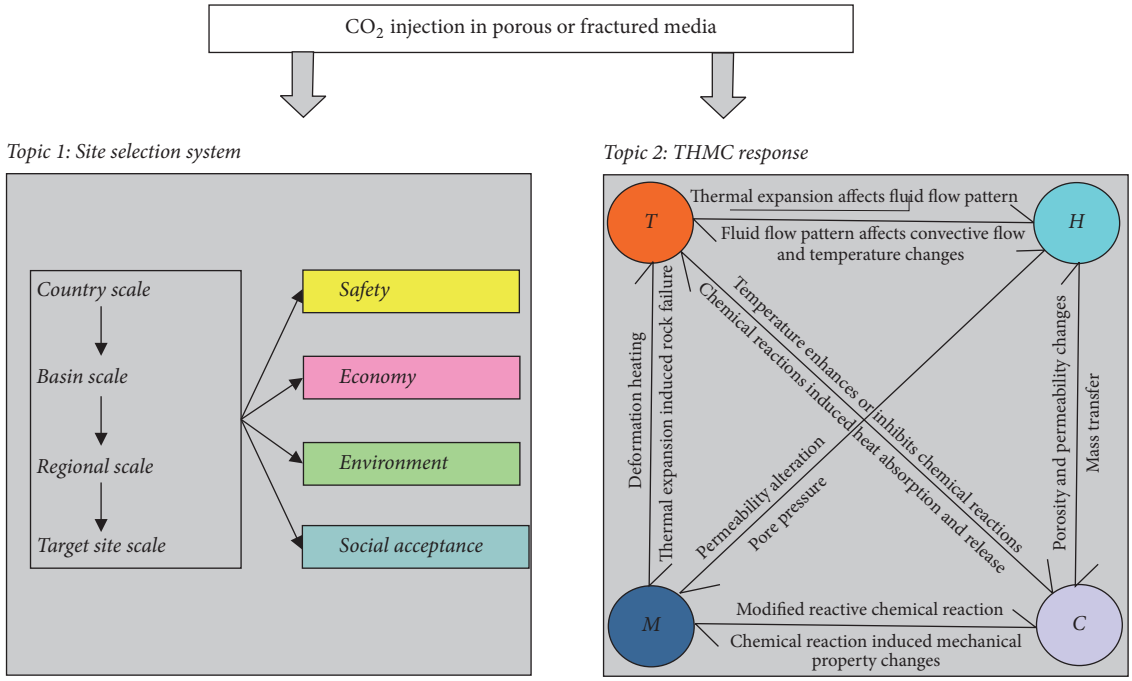

Figure 2: Schematics of the two main topics, that is, the site selection system (1) and the THMC responses (2) associated with CCS and CCUS technologies.

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, and so on [42–44, 49–52]. Nevertheless, the maturity of its commercial application is still very low. Pilot-scale CO_2-ECBM projects so far include those in Alberta, 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 [53].

2.4. CCUS: CO_2-EGR. Studies on injecting CO_2 into depleted gas reservoirs to enhance gas recovery started in the 1990s [54]. Unlike the CO_2-EOR technology, CO_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, and so on [55–60]. For some CO_2-EGR projects, the gas recovered can reach 10%, while other projects have seen less or no enhancement [61–63]. The rapid breakthrough of CO_2 in a production well, resulting in a high concentration of CO_2, restricts the production of pure natural gas [64]. Since 1999, the USA has carried out a pilot project of CO_2-EGR in Rio Vista. The Netherlands injected 60 kilotonnes of CO_2 into a depleted gas reservoir in the K12B project during 2004 and 2009 [7]. The CLEAN project in Germany started a CO_2-EGR project in the Altmark gas fields in 2009; however, public protests have prevented CO_2 injection on the site [65]. Many other countries including Australia and Norway are also positively developing this technology [64, 66–74].

2.5. CCUS: CO_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 multistaged fracturing technology. The revolution of shale gas in the USA is changing the energy structure of the world [75].

Encouraged by the successful application of CO_2 in oil and gas recovery, its application in aiding the production of shale gas began in recent years [76–81]. There has also been progress in replacing water by supercritical CO_2 as the injection fluid in the fracturing technology [82–86]. However, this process is still in the very early exploration stages.

2.6. CCUS: CO_2-EGS. The first study of EGS technology started in Fenton Hill, USA, in 1970 [87]. Since then, many other countries, including France, Germany, Austria, Italy, Japan, and Australia, 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 [88], CO_2 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., [89–93]).

The application of CO_2 in a geothermal system is not restricted to the hot dry rock reservoirs but also includes the conventional hydrothermal reservoirs [38, 91, 94]. The injection of CO_2 can enhance the efficiency of reinjecting the hot wastewater by improving the porosity and permeability

through the activated water-rock geochemical reactions [95]. Besides being the main circulation fluid, CO_2 can also be regarded as a pressurized hydraulic fluid in the reservoir. Injection of CO_2 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 CH_4 dissolved in the aquifer water [96–99]. Reference [38] described this process as the CO_2-AGES (CO_2-aided geothermal extraction system) in which three stages are involved: (1) the production of hot water when CO_2 is used as the pressurized hydraulic fluid; (2) two-phase fluid flow in the production well after the CO_2 breakthrough; and (3) and as a circulation fluid, when CO_2 fills the production well, which is similar to CO_2-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 CO_2-EOR and the other 3 projects are pure CO_2 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 Figure 3 for more details.

There are still no concrete CO_2-ESG and CO_2-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 [100, 101]. 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 [102]. The EGS technology is still at the research and development stage. Nevertheless, there are some experimental EGS plants and pilot projects, for example, at Fenton Hill, Coso, and Desert Peak in the USA, Bad Urach, Neustadt-Glewe, Bruchsal, Landau, and Unterhaching in Germany, and Soultz-sous-Forets and Bouillante in France [87]. Substantially higher research, development, and demonstration efforts are needed to ensure EGS technology becomes commercially viable in the near future.

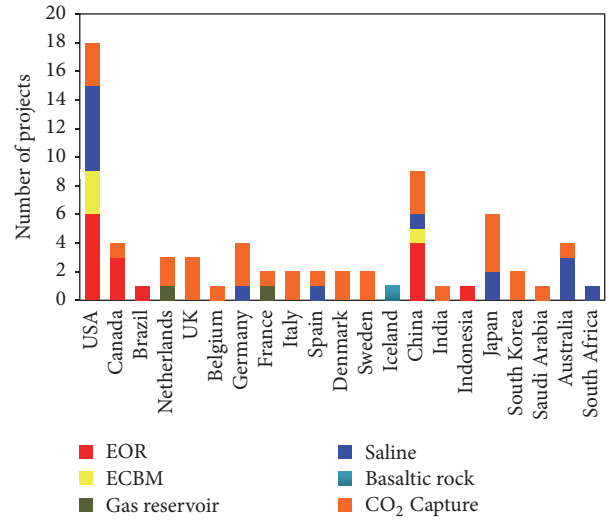

Figure 3: Global distribution of pilot-scale CCUS engineering projects based on project purpose and reservoir types, data sourced from http://www.globalccsinstitute.com/.

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 [103]. Meanwhile, more attention has been paid to CCUS technology, especially CO_2-EOR and CO_2-ECBM [104–107]. Between 2006 and 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 CO_2-EOR and the others to the CO_2 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 (Figures 4 and 5 and Table 1), the distribution of funding for different aspects of CCS and CCUS is shown as follows: (1) CCS (32 projects), of which all the 7 projects funded by the MOST were related to CO_2 capture technology. The 23 projects funded by the NSFC and 1 project funded by the Ministry of Land and Resources were concerned with CO_2 storage; (2) CCUS: CO_2-EOR (18 projects), of which 6 projects were funded by the MOST and 10 by the NSFC; (3) CCUS: CO_2-ECBM (22 projects), of which 3 projects were funded by the MOST, and 17 by the NSFC; (4) CCUS: CO_2-EGR (4 projects); (5) CCUS: CO_2-ESG (4 projects); and (6) CCUS: CO_2-EGS (7 projects).

Several international cooperation research projects were also developed, including NZEC between China and Europe, CAGS between China and Australia, and CCERC between China and the USA; see Table 2 for further details.

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

Name of the research projects	Responsible institute	Funding sources	Amount
Type 1: CO_2-EOR			
Utilization of CO_2-EOR and geological storage of CO_2	Research Institute of Petroleum Exploration & Development (CNPC)	973 Program 2006–2010	3500
Key technologies of CO_2-EOR and sequestration		863 Program 2009–2011	—
Basic research on CO_2 geological sequestration, reduction in CO_2 emission and utilization		973 Program 2011–2015	—
Key technologies of CO_2-EOR and storage		Major Science & Technology 2011–2015	—
Microscopic mechanism of oil-water-rock multiple surface system of the porous media and their application	Tsinghua University	NSFC 2016 confirmed	20
CO_2 capture and storage technologies		2008–2010	—
Basic studies on the transportation of supercritical CO_2, water and oil in the low permeable porous media	Dalian University of Science and Technology	NSFC 2008–2011	180
Studies on microscopic flowing mechanism of supercritical CO_2, oil and water in the low permeable oil reservoir		NSFC 2013–2015	25
Studies on the CO_2 diffusion and mass transfer processes in oil and water bearing porous media		NSFC 2013 confirmed	25
Factors affect the CO_2 diffusion in the porous media and its mechanism studies	China University of Petroleum	NSFC 2009–2011	20
QSAR studies on the thermodynamics and transportation properties of CO_2-EOR system	Tianjin University	NSFC 2012–2014	—
CO_2-EOR and its damage mechanism to the reservoir	China University of Geosciences	NSFC 2012–2015	59
Studies on the surface properties using alkylol amine capture CO_2 and processes of CO_2-EOR	North China Electric Power University	NSFC 2012–2016	—
Microscopic mechanism, quantification and optimization of injection-production scheme of CO_2-EOR and CO_2 sequestration in the oilfield	Southwest Petroleum University etc.	NSFC 2014–2016	25
CO_2-EOR pilot project in Jilin oilfield	Jilin oilfield etc.	2007-	—
CO_2-EOR process and pilot project in Songliao basin		Major Science & Technology 2011–2015	—
CO_2 capture and CO_2-EOR pilot project in Shengli oilfield	Shengli oilfield etc.	2010-	—
Technical development of CO_2 capture from the flue gas of the large-scale coal-fired power station, EOR and storage and pilot projects		Major Science & Technology 2012–2016	—
CO_2 capture from coal gasification and EOR		Independent project	—
Type 2: CO_2-ECBM			
CO_2 storage and enhanced coalbed methane recovery	China United Coalbed Methane Corp., Ltd. etc.	International 2002–2007	—
CO_2 injection and storage in the deep coal seam and enhanced coalbed methane recovery		International 2011–2015	—
Test project of deep coalbed methane production technology of China United Coalbed Methane Corp. Ltd. (CUCMC)		Major Science & Technology 2011–2015	—
CO_2-ECBM potential in China and related basic scientific research issues	Institute of Rock and Soil Mechanics (CAS)	One hundred talent program 2005–2009	—
CO_2-ECBM potential in China and the suitability evaluation		GSC 2011	—
Mechanism of using mixtures of CO_2/N_2 displace coalbed methane in situ geological conditions and the best ratio of gas composition		NSFC 2012–2014	26
Impacts of coal matrix on the coal expansion and permeability changes of CO_2/CH_4 during the CO_2-ECBM process	Institute of Coal Chemistry (CAS)	NSFC 2007–2009	—
Solid-gas interaction during CO_2 sequestration in the deep coal seam and simulation of the sequestration experiment	Institute of Process Engineering (CAS)	NSFC 2007–2009	32

Table 1: Continued.

Name of the research projects	Responsible institute	Funding sources	Amount
Advanced models of CO_2-ECMB	China University of Mining and Engineering	NSFC 2007-2008	6
Adsorption and desorption mechanisms of multiple gases during CO_2-ECBM process		NSFC 2003–2005	
Experimental study of coal matrix on expansion effects during CO_2-ECBM process		NSFC 2008–2010	—
Two-phase gas and solid coupling effect and dual porosity effect during the CO_2 sequestration in the deep coal seam		NSFC 2011–2013	20
THM coupling mechanism of CO_2-ECBM		NSFC 2012–2014	25
Dynamic model of multiphase fluid CH_4-water flow in porous media of heterogeneous coal seam		NSFC 2012 confirmed	25
Fluid-solid coupling response and mechanism of supercritical CO_2 and minerals in the coal		NSFC 2013 confirmed	25
Theoretical study of CO2 sequestration in the deep coal seam and the efficiency of CH_4 recovery		NSFC 2014 confirmed	300
Interaction of supercritical CO_2 and organic matter in the coal and their responses to the coal structure		NSFC 2014 confirmed	25
The construction of 3D model of reservoir structure in the high grade coal and the geochemical response to the injection of CO_2		NSFC 2014 confirmed	23
CO_2 enhances CH_4 adsorbed by the coal, the permeability characteristics and mechanisms		NSFC 2015 confirmed	70
Multiphase gas-liquid-solid coupling mechanisms of CO_2 sequestration in the porous coal media		NSFC 2016 confirmed	62
Interaction of supercritical CO_2 and coal during CO_2 sequestration in the deep coal seam and its impact on the CO_2 storage	Shandong University of Science and Technology	NSFC 2012–2015	60
Transportation mechanisms of supercritical CO_2 injection into the stress partition residual coal pillar and its displacement of CH_4		NSFC 2015 confirmed	20
Basic research on the mechanism of CO_2-ECMB in the deep low permeable unmineable coal seam under THM coupling effect	Liaoning Technical University	NSFC 2009–2011	33
Microscopic mechanism of supercritical CO_2 on the recovery of CH_4 in the coal		NSFC 2014 confirmed	25
Type 3: CO_2-EGR			
Safety production of the CO_2 bearing gas reservoir and the utilization of CO_2	Research Institute of Petroleum Exploration & Development	Major Science & Technology 2008–2010	—
Pilot project of the production of the CO_2 bearing volcanic gas reservoir and utilization	Jilin oilfield etc.	CNPC 2008–2010	—
CO_2 sequestration mechanism in the depleted gas reservoir and the transportation rules	Southwest Petroleum University	NSFC 2013 confirmed	80
Phase behavior of supercritical CO_2 displacing CH_4 in the porous media and the seepage characteristics	Dalian University of Technology	NSFC 2015 confirmed	64
Type 4: CO_2-ESG			
Basic research of supercritical carbon dioxide enhanced shale gas development	Wuhan University	973 Program 2014–2018	—
Basic research of the supercritical CO_2 in the production of unconventional oil and gas reservoirs	China University of Petroleum	NSFC 2011–2014	258
CO_2 sequestration in the shale gas reservoir and mechanisms of CO_2-CH_4-shale interaction		NSFC 2013–2015	25
Damage mechanism of using supercritical CO_2 as the hydraulic fluid in the shale reservoir	Chongqing University	NSFC 2014 confirmed	25
Studies on the solid-fluid coupling mechanisms of CO_2 sequestration in the shale reservoir and its effect on the recovery of shale gas		NSFC 2014 confirmed	80
Brittle fracturing mechanism of supercritical CO_2 used as the hydraulic fluid in the shale reservoir and the transportation rule of the suspended sand	Qingdao University of Science & Technology	NSFC 2014–2016	80
The propagation evolution of the hydraulic fracture network induced by the supercritical CO_2 in the shale reservoir	Institute of Geology and Geophysics (CAS)	NSFC 2015–2017	85
Type 5: EGS/CO_2-EGS			
Simulation and prediction of CO_2-EGS	Jilin University etc.	Ph.D. program 2011–2013	—
Comprehensive utilization and production of hot dry rocks		863 Program 2012–2015	—

Table 1: Continued.

Name of the research projects	Responsible institute	Funding sources	Amount
The flowing characteristics of the man-made fractures in the hot dry rocks and the mechanisms of multifield coupling heat and mass transfer	Tianjin University	NSFC 2013 confirmed	76
Large scale CO_2 utilization and storage in the innovative EGS technology	Tsinghua University	International 2012–2014	—
Mechanisms of the production of geothermal energy in the high temperature depleted gas reservoir using CO_2 as the circulation fluid and the evaluation of potential	China University of Petroleum	NSFC 2016 confirmed	54
Heat transfer using supercritical CO2 enhances the geothermal recovery and the mechanisms of induced sliding of fractures	Institute of Rock and Soil Mechanics (CAS)	NSFC 2016 confirmed	54
Multiphase dynamic characteristics in the CO_2 plume type geothermal system and the optimization of the energy conversion	Jilin Jianzhu University	NSFC 2016 confirmed	20
Type 6: CO_2 capture technology			
R&D of the new type O_2/CO_2 circulated combustion equipment and the optimization of system	Huazhong University of Science and Technology	863 Program 2009–2011	—
Key technologies of CO_2 capture by using 35 MWth oxy-fuel combustion technology, R&D in equipment and pilot projects		National Sci-Tech support plan 2011–2014	—
R&D in key technologies of CO_2—oleaginous microalgae—biodiesel	Xin'ao Group etc.	863 Program 2009–2011	2070
IGCC-based CO_2 capture, utilization and sequestration technologies and pilot projects	Huaneng Group etc.	863 Program 2011–2013	5000
CO_2 capture and purification technology using high gravity method	Shengli oilfield etc.	National Sci-Tech support plan 2008–2010	—
Capture of high concentration of CO_2 in 0.3 million tons coal to oil industry, geological sequestration technology and pilot scale project	Shenhua Group etc.	National Sci-Tech support plan 2011–2014	—
Development of key technologies of reduction in CO_2 emission from the blast furnace iron making and their utilization	China Association of Metal	National Sci-Tech support plan 2011–2014	—
Research on key technologies related with large-scale CO_2 capture from the flue gases of the coal-fired power station	Tsinghua University	NSFC 2012 confirmed	230
Type 7: CO_2 storage in the saline formation (CCS technology)			
Potential assessment of CO_2 geological storage in China and pilot projects	China Geological Survey	Ministry of Land and Resources 2010–2014	—
Multiphase multicomponent reactive transportation mechanism of the sequestration of impure CO_2 and numerical simulation	Institute of Rock and Soil Mechanics (CAS)	NSFC 2016 confirmed	20
HMC coupling mechanism of CO_2 sequestration in the saline formations, stability of rock and the transportation rules of CO_2		NSFC 2011 confirmed	20
Geochemical studies on the supercritical CO_2-rock-saline water system	China University of Geosciences	NSFC 2011–2013	50
Mechanisms of the water-rock-gas interaction of the CO_2 sequestration in the saline aquifers in the pressurized sedimentary basin		NSFC 2012–2014	70
Experimental geochemical studies on the interaction of supercritical CO_2-water-basalt	Nanjing University	NSFC 2013–2015	85
Surface characteristics of supercritical CO_2-saline water in CO_2 geological sequestration	Dongnan University	NSFC 2012–2014	25
The diffusion mechanism of CO_2 in porous media and its quantitative relationship with the propagation rate of the CO_2 front	China University of Petroleum	NSFC 2013 confirmed	80
Factors affect the diffusion and mechanism of CO_2 in porous media		NSFC 2009 confirmed	20
Numerical simulation of the multiple field coupling processes in CO_2 geological sequestration using numerical manifold method	Beijing University of Technology	NSFC 2012 confirmed	62
Evolution of the damage in the near-field neighboring rocks of the CO_2 storage site in the rock salt and the integrity studies	Sichuan University	NSFC 2012 confirmed	25
Transportation rule and trapping mechanisms of CO_2 geological sequestration in the multiscale heterogeneous saline formations	Hehai University	NSFC 2012 confirmed	58
Impacts of reservoir heterogeneity on the capacity of CO_2 in the saline formations	Wuhan University	NSFC 2013 confirmed	25

Table 1: Continued.

Name of the research projects	Responsible institute	Funding sources	Amount
Flowing characteristics and mechanism of the supercritical CO_2 in the low permeable porous media	Qingdao University of Science & Technology	NSFC 2014 confirmed	80
Mechanism studies on the physical and dissolution trapping of the supercritical CO_2 in the microscopic porous aquifer	Tsinghua University	NSFC 2010 confirmed	20
Interaction of CO_2-saline water-caprocks in the CO_2 geological sequestration and the risk of CO_2 leakage		NSFC 2014 confirmed	84
Mechanisms of the difference in the distribution of the CO_2 saturation based on the high reliable saline formation model	GSC Hydrogeology & Environmental Geology	NSFC 2016 confirmed	18
Physical property measurements on the CO_2-saline water system in the CO_2 geological sequestration		NSFC 2011 confirmed	20
Impacts of the physical properties of the porous media on the two-phase (CO_2, saline water) fluid flow and the trapping mechanism of CO_2		NSFC 2014 confirmed	80
Two-phase CO_2-water fluid flow characteristics and trapping mechanism of CO_2 at the porous scale in the multiple porous media	Dalian University of Technology	NSFC 2015 confirmed	64
The convective mixing of CO_2 sequestration in the saline formations and its development characteristics		NSFC 2015 confirmed	21
Basic studies on the transportation of supercritical CO_2 in the geological sequestration in the saline formations		NSFC 2012 confirmed	25
Basic research on the wettability of CO_2-saline water-rock equilibrium system during the CO_2 sequestration in saline formations		NSFC 2013 confirmed	25
Viscous behavior and mechanism of the supercritical CO_2 on the rock surface in the geological sequestration condition		NSFC 2016 confirmed	60

Table 2: China's international collaboration on CCUS projects during 2005–2016.

Name of projects	Main responsible institutes in China	Funding sources	Funding
China-EU Cooperation on Near Zero Emissions Coal (NZEC)	The Administrative Center for China's Agenda 21 (ACCA21) etc.	MOST, EU, UK Environment, Food and Rural Affairs (DEFRA) 2007–2009	4.5 million US$
China-Australia Geological Storage of CO_2 (CAGS)		MOST, Australian Department of Resources, Energy and Tourism 2010–2018	>4.0 million US$
China-Italy CCS project		MOST, Italian Ministry of Environment 2010–2012	—
China-Netherlands CO_2-ECBM and CO_2 saline aquifer storage exchange center	Institute of Coal Chemistry (CAS) etc.	Ministry of Economic Affairs 2008-	—
China-U.S. low emission technology of IGCC	Institute of Engineering Thermophysics (CAS) etc.	MOST, U.S. DOE 2010–2012	—
China-U.S. Clean Energy Research Center (CCERC)	Huazhong University of Science and Technology	MOST, U.S. DOE 2010–2015	2 million US$/year
China-Germany CCUS project	Sichuan University etc.	NSFC, DFZ 2010–now	—

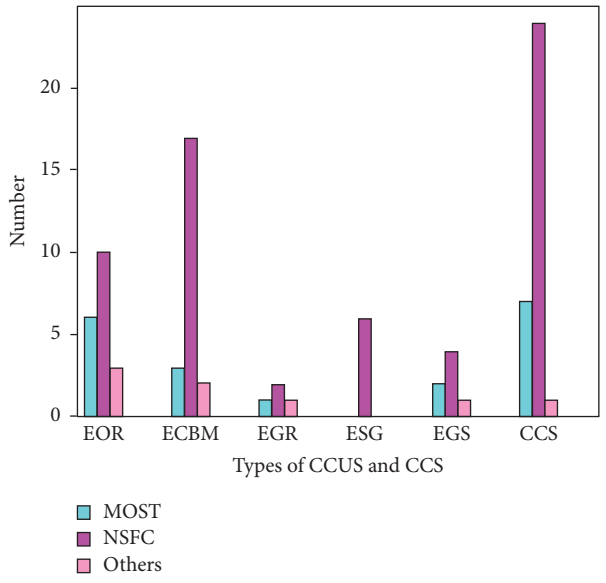

Figure 4: Research projects of CCS and CCUS in China during 2005–2016 based on Table 1.

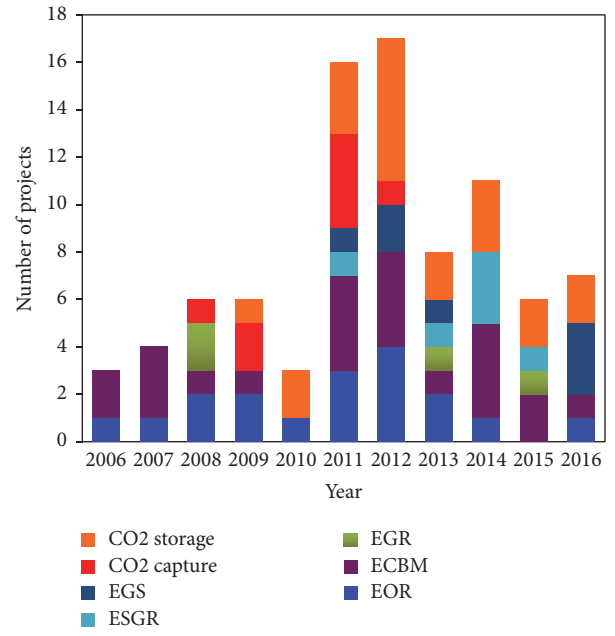

Figure 5: Different types of CCUS research projects in China during 2006–2016 based on Table 1.

4.1. 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, 108–112]. Combined with a selection indicator evaluation system for potential storage sites, the standardization of the CCS in China has a good foundation [20, 21, 113, 114]. A preliminary evaluation of the CO_2 storage potential in the saline formations at a depth of 1–3 km showed a capacity of 1.435×10^{11} tonnes, and most parts of the Huabei plain and Sichuan Basin can be regarded as favorable storage sites [115, 116]. Based on the studies on CO_2 sequestration in saline formations [117–124], 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 CO_2 injected in 2010 [125–130].

4.2. CCUS: CO_2-EOR in China. The theoretical CO_2 storage capacity of depleted onshore oil reservoirs is estimated to be 3.78 gigatons of CO_2 [131]. Conservative estimates reveal that

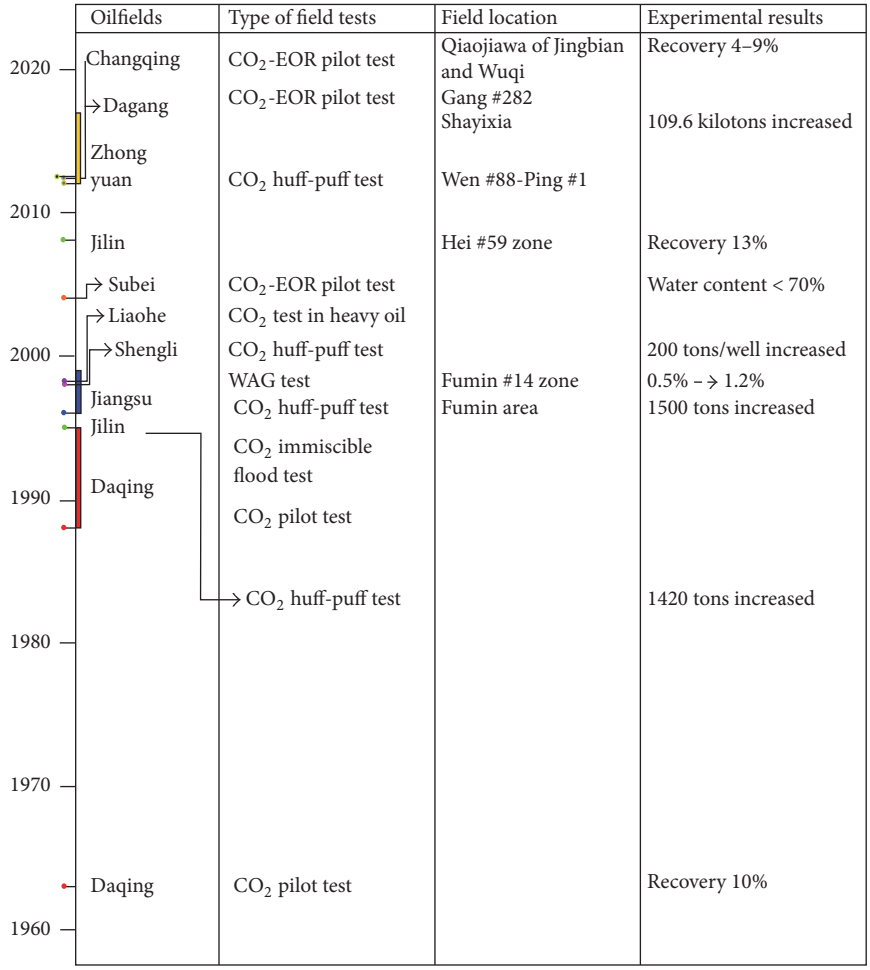

FIGURE 6: Development of CO_2-EOR pilot tests in several oilfields in China since the 1960s.

about 70% of the oil production comes from nine oilfields, that is, 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 [132]. Several CO_2-EOR field tests have also been carried out in other fields including Jilin, Dagang, Shengli, and Liaohe (see Figure 6), with recovery increasing to about 10% [118, 121, 132–137]. 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 [138]. 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.

4.3. 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 [139–145]. This research was further extended to include the CH_4 displacement mechanisms by using a mixture of CO_2 and N_2 [41, 146–151]. 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% [152]. Based on the preliminary evaluation of [153], 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 to 1500 m.

4.4. CCUS: CO_2-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 CO_2 sequestration, there will be a potential for a CO_2 storage capacity of 5.18 billion-tons [9, 154]. 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 CO_2-EGR technology. From the maturity point of view of this technology, very few research institutes in China are working on the improvement of CO_2-EGR at the present. Furthermore, the early breakthrough of CO_2 in gas production wells makes it difficult to attain good production efficiency from the application of CO_2-EGR technology [47]. A means of reducing the costs of separating the mixed gases, CO_2 and CH_4, is required to attain the widespread application of the CO_2-EGR technology in China.

4.5. CCUS: CO_2-ESG in China. Encouraged by the successful exploitation of shale gas in North America, China joined the exploration of shale gas in 2005 [155]. The published data from the Ministry of Land and Resources in 2002 confirms that China had a shale gas reserve of 25.1×10^{12} m^3. By the end of 2015, China had a technical shale gas reserve of about 1.3×10^{11} m^3 including the increased proved technical reserve of 1.09×10^{11} m^3.

In December 2010, China drilled its first shale gas exploration well, Wei201 in Weiyuan gas field [155]. 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 2.5×10^7 m^3, which increased to 2.0×10^8 m^3 in 2013, 1.3×10^9 m^3 in 2014, and 4.47×10^9 m^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^{11} m^3. It has produced shale gas of about 1.03×10^9 m^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 [102]. In 2012, the National Energy Administration of China set a target for shale gas production of 6×10^{10}–1.0×10^{11} m^3 by 2020. But after a two years' practical experience during 2012-2013, it revised this target to 3.0×10^{10} m^3 by 2020. Using CO_2 to enhance the recovery of shale gas is now at an early exploration stage [156].

4.6. CCUS: CO_2-EGS in China. The 863 plan project that aims at investigating EGS was initiated by Jilin University in 2012 [157]. There are now several other projects in the country using CO_2 in geothermal production (see Table 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., [143, 158–162]) have already studied the operation mechanisms of the CO_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 Figure 2.15, [34]. Therefore, pilot-scale CCUS (mostly CO_2-EOR) engineering projects in China are also located in these regions (Figure 7, Table 3). 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 are 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 for the exploitation of the CO_2-rich (21% CO_2 concentration) Changling gas field. 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 [137]. 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 ultralow permeable oil reservoir through 11 injection wells by April 2015.

(4) A CO_2-EOR project operated by Zhongyuan oilfield (still in operation) injected CO_2 at a rate of 30,000 tons/year and managed to increase oil production by 3600 tons after injection of 2170 kilotons of CO_2 and 827 kilotons of water [7]. By February 2017, a total amount of about 553 kilotons of CO_2 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 CO_2-EOR project led by the Yangchang oilfield company was carried out in 2013 using captured CO_2 during the production of methanol and acetic acid. At present, the capture equipment designed for 360 kilotons/year of CO_2 is under construction. Pilot-scale CO_2-EOR field tests have been done in some

Table 3: Main engineering CCUS projects in China.

Projects	Location	Scale tons/yr	CO_2 capture method	Storage/utilization	Status
(1) CO_2-EOR project by Daqing oilfields	Yushulin, Hailaer	—	—	EOR	Operation
(2) CO_2-EOR project by Jilin oilfield	Songyuan	0.28 million	Liquefaction of FCC flue gas	EOR	Operation
(2-1) Second stage of EOR project in Jilin oilfield	Songyuan	Planned for 0.5 million	Precombustion from the separation of natural gas production	EOR	Operation
(3) CO_2-EOR project by Shengli oilfield	Dongying	40,000	Postcombustion	EOR	Operation
(4) EOR project by Zhongyuan oilfield	Puyang	100,000	Post-combustion	EOR	Operation
(5) EOR project by Yanchang oilfield	Yanchang	400,000	Coal liquefaction plant	EOR	Operation
(6) First stage of Huaneng greengen IGCC in Tianjin	Tianjin	—	Pre-combustion	Planed for EOR	Operation
(7) CO_2-ECBM by China United Coalbed Methane Ltd.	Jincheng	40/day	Purchase of CO_2	ECBM	Completed
(8) Full chain CCS project by Shenhua Group	Ordos	100,000	Coal liquefaction plant	Saline formation	Completed
(9) Pilot project of IGCC clean energy in Lianyungang	Lianyungang	1000,000	Pre-combustion	Planed in saline formation	Preparation
(10) 35 MWt oxy-fuel combustion in Zhongyan Yingcheng of Hubei	Yingcheng	100,000	Oxy-fuel combustion	Sequestration in the salt rock	Preparation
(11) CO_2 capture and storage pilot project by China Resources Power	Dongguan	1 million	Pre-/post-combustion from power station and oil refinery	Planed for EOR or saline formation	Prefeasibility study
(12) Coal-to-liquids project in Ningxia by Shenhua Group	Ningxia	2 million	Pre-combustion from the coal-to-liquids process	Undefined	Opportunity study
(13) Third stage of Huaneng greengen IGCC in Tianjin	Tianjin	2 million	Pre-combustion from the power station	Planed for EOR saline formation	Not start
(14) Second stage of coal-to-liquids project by Shenhua Group	Ordos	1 million	Pre-combustion from the coal-to-liquids process	Saline formation	Prefeasibility study
(15) CCS project by Sinopec Qilu Petrochemical	Dongying	0.5 million	Pre-combustion from oil refinery	EOR	Preliminary design
(16) CCS project of Shengli power station by Datang Group	Dongying	1 million	Post-combustion from the power station	EOR	Prefeasibility study
(17) CO2 capture and EOR in coal chemical industry by Yangchang Petroleum Co. Ltd.	Yanchang	5,0000	Pre-combustion from coal chemical industry	EOR	Operation
(17-1) Second stage of CO_2 capture and storage project by Yanchang Group	Yanchang	1 million	Pre-combustion from coal chemical industry	EOR	Not start
(18) CO_2 capture and storage pilot project in Daqing oilfield by Datang Group	Daqing	1 million	Oxy-fuel combustion from the power station	Planed for EOR + saline formation	Prefeasibility study
Coal-to-gas project by CNOOC Datong *	Datong	1 million	Pre-combustion from coal-to-gas process	Planed for EOR + saline formation	Prefeasibility study
Coal-to-gas project by CNOOC Ordos*	Ordos	1 million	Pre-combustion from coal-to-gas process	Planed for EOR + saline formation	Pre-feasibility study

Table 3: Continued.

Projects	Location	Scale tons/yr	CO_2 capture method	Storage/utilization	Status
Coal-to-olefin Ordos project by CPIC and TOTAL*	Ordos	1 million	Pre-combustion from coal-to-olefin process	Planed for EOR + saline formation	Prefeasibility study
CCUS project by Shanxi international energy group*	Shanxi	2 million	Oxy-fuel combustion from the power station	Undefined	Prefeasibility study
Industrial conversion of the captured CO_2, not for underground geological sequestration					
(19) Pilot project of CO_2 sequestration by microalgae of Xin'ao Group	Dalate qi	320,000	Flue gas of the coal chemistry factory	Microbe sequestration	Construction
(20) SNG project in Qinghua of Xinjiang	Yili in Xinjiang	—	Pre-combustion	Microbe sequestration	Operation
(21) Geothermal power station in Gaobeidian of Beijing by Huaneng	Beijing	3000	Post-combustion	Food and industry use	Operation
(22) Shidongkou project in Shanghai by Huaneng	Shanghai	120,000	Post-combustion	Food and industry use	Operation
(23) Shuanghuai power plant project	Chongqing	10,000	Post-combustion	N/A	Operation
(24) CO_2 project in Hainan	Dongfang	2100	Separation from natural gas	Biodegradable plastics	Operation
(25) CO_2 project in Jiangsu	Taixing	8000	Alcohol factory	Chemical material	Operation
(26) CO_2 pilot project in Tianjin	Tianjin	20,000	Post-combustion	Food	Preparation

Note. Projects marked with ∗ threaten cancellation in the near future for unknown reasons.

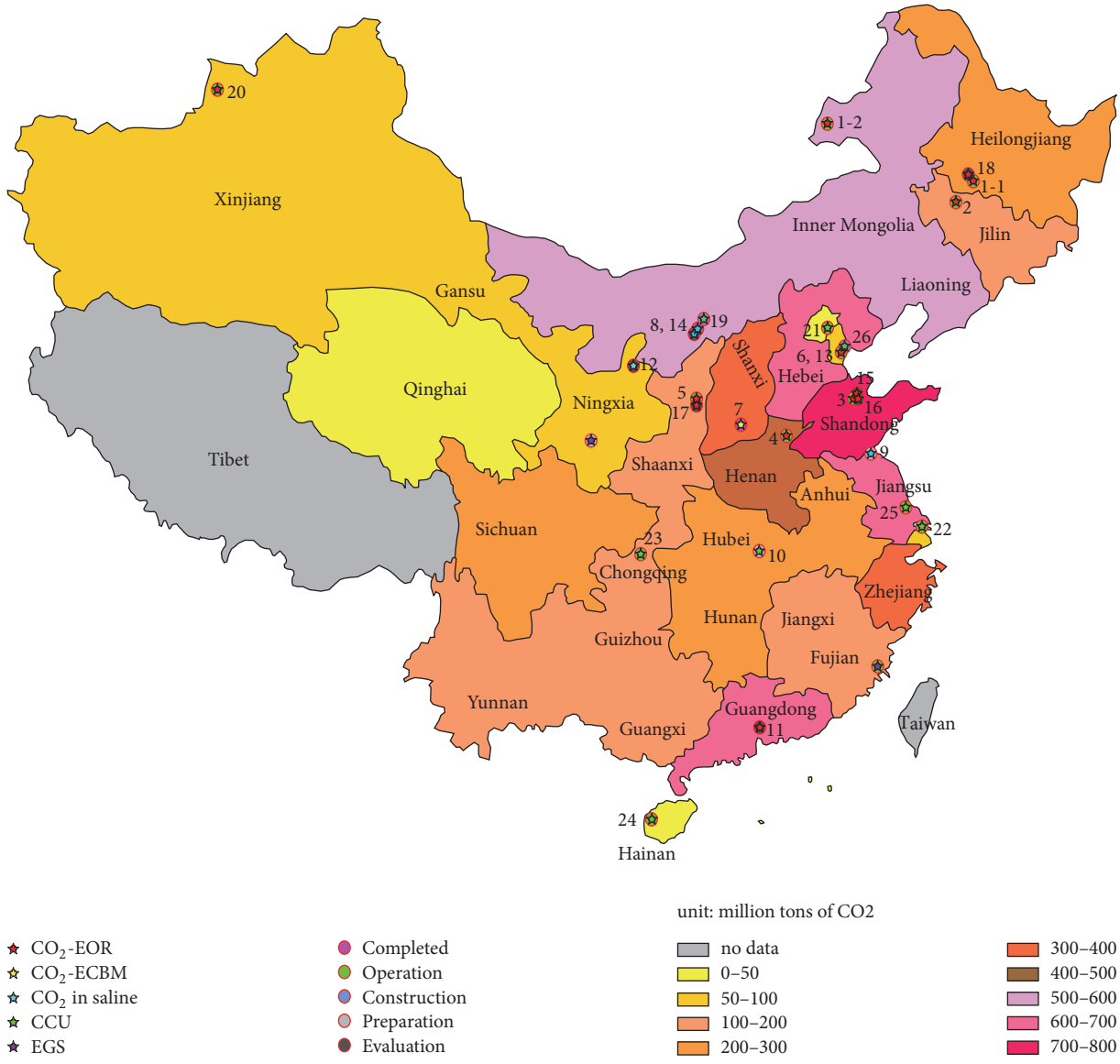

FIGURE 7: Distribution of CCUS engineering projects in China excluding the South China Sea Islands (numbers defined in Table 3) superimposed on the provincial CO_2 emission map for the year 2010 (from [34]).

districts of Jinbian and Wuqi, with a total of 90 kilotons CO_2 injected.

(6) As the first demonstration of IGCC power station in China, the first stage of the IGCC project at Tianjin combined with the CO_2 capture and EOR technology, with an installation capacity of 265 MW, has been in operation since November 2016.

(7) The CO_2-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 CO_2-ECBM field test in China and operates at an injection rate of 40 tonnes/day of CO_2. This is a cooperation project between the Zhonglian coalbed methane Ltd and Canada which aims at studying the feasibility of CO_2-ECBM in China [53].

(8) The full chain CCS project in the saline formations located in the Ordos of 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 CO_2, 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 to 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.

(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 → preliminary → prefeasibility → feasibility → construction drawing design → construction → operation → completed. All the stages before the construction drawing design phase, that is, 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 prefeasibility 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 present, China does not execute any CO_2-EGS field tests. 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 [157]. 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 to CO_2-EGR and CO_2-ESG in China.

6. Challenges in the Widespread Application of CCUS in China

6.1. 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/ultralow 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 [138]. 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 [132].

(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 like the adsorption-desorption process between CH_4 and CO_2 in the coal seam [46, 146, 147], the mechanisms of the interaction between CO_2-CH_4-H_2O at molecular scale [150], the impact of the coal grade, water content and composition of coal, and so on on the diffusion and migration of mixed gases in the coal seam, the dynamic changes of phase behaviour during the process of CO_2 injection, and CH_4 production and so on.

(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 like 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, and so on [48, 60].

(d) Multistage 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 CO_2 to extract brine or methane energy from the aquifers was also studied recently [168]. While the feasibility of using CO_2 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. Technologies including CO_2-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.

6.2. Negative Impacts on the Environment and Resources. The risk of leakage of the injected CO_2 in the injection/production wells may have a serious environmental impact [169–173]. The groundwater quality may deteriorate if the CO_2 in the injection layer leaks into the freshwater aquifer through microfractures 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 [104]. The dynamic migration process of CO_2, chemical interaction among CO_2 -reservoir fluid-rock, the deformation or eruption of injection/overlying caprocks, and temperature and pressure changes in the reservoir should be monitored for a long time after the injection [29, 176].

6.3. Storage Capacity Data Is Not Clear. The total amount of resources and the distribution of depleted oil and gas fields, deep unmineable 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, and so on.

6.4. Policy Factor. The positive effect of China's involvement in CCUS technologies in recent years has been to focus on developing CO_2-EOR, the capture of CO_2, the shale gas and hot rock geothermal energy production, and especially shale gas production with a subsidy of 4 US¢/m^3 during 2016–2018 and 3 US¢/m^3 during 2019-2020. However, other fields of CCUS also need to be supported by the government.

6.5. High Investment Costs. The cost of a CCS or CCUS project mainly includes CO_2 capture, transportation, drilling, injection, and monitoring. Costs for the capture of CO_2 produced by the technologies of precombustion, postcombustion, 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 CO_2 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 CO_2 capture technology, respectively, [178]. Depending on different situations and technologies in US, the capture cost is 42–87 US$/ton CO_2, transportation costs range from 4.3 to 7.2 US$/ton CO_2/250 km, while injection and storage costs are 1–12 US$/ton CO_2 based on the prices in 2013. In China, the cost of electricity generation by coal-fired power station increases by 30%–50% using CO_2 capture technology due to the extra consumption of electricity and steam. Taking the Huaneng Beijing coal-fired power station as an example, the capture price is about 24.3 US$/ton CO_2, with the CO_2 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 to 24.8 US$/ton CO_2, accounting for 80% of the price of a full-scale CCS project [180, 181]. However, the uncertainty in the CO_2 capture price is high depending on different capture technologies including precombustion, postcombustion, and oxy-fuel combustion at various stationary point sources including coal-fired power stations, cement factories, and coal chemical industries. From the aforementioned point of view, the uncertainty in the investment of a specific CCS or CCUS engineering project is determined by the cost of CO_2 capture. Therefore, a reduction in the cost of CO_2 capture is the key to the widespread application of CCS or CCUS technologies. Besides, drilling costs are large for all types of CCUS engineering projects and hydrocarbon/geothermal production, taking a shale gas well as an example, it costs 5.8 million US$ 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].

6.6. 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.

6.7. 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, and so on 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 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, and geothermal energy.

(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 ultralow 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 favorable physical properties including large density and small viscosity. 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.

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:	CO_2 Large-scale Enhanced Gas Recovery project in the Altmark Natural Gas Field
CNOOC:	China National Offshore Oil Corporation
CNPC:	China National Petroleum Corporation
CO_2-AGES:	CO_2 aided geothermal extraction system
CO_2-ECBM:	CO_2 enhanced coalbed methane recovery
CO_2-EGR:	CO_2 enhanced gas recovery
CO_2-EOR:	CO_2 enhanced oil recovery
CO_2-ESG:	CO_2 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 Friesenpferdezuchter
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:	International Energy Outlook
IGCC:	Integrated Gasification Combined Cycle (IGCC)
IPCC:	Intergovernmental Panel on Climate Change
K12B:	K12B gas field located at the North Sea
MOST:	The Ministry of Science and Technology of China
NSFC:	The National Natural Science Foundation of China
NZEC:	China-EU Cooperation on Near Zero Emissions Coal project
RECOPOL:	Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian Coal Basin of Poland
SNG-EOR:	Synthetic Natural Gas-Enhanced Oil Recovery
USDOE:	United States Department of Energy.

Conflicts of Interest

The authors hereby declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors would like to extend their gratitude to the National Natural Science Foundation of China (Grant no. NSFC51374147) and China CDM Fund "Update of China's CCUS Technical Roadmap" (Grant no. 2013085) for funding this work. Q. Li acknowledges financial support from the China-Australia Geological Storage of CO_2 (CAGS) Project funded by the Australian Government under the auspices of the Australia China Joint Coordination Group on Clean Coal Technology.

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