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CO_2-EOR in China: A comparative review

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ABSTRACT

Given China's economic dependence on coal for energy and industry, carbon capture, utilization and storage (CCUS) technology is a critical decarbonization strategy. Carbon dioxide (CO_2) enhanced oil recovery (EOR) is critical to success of CCUS in China, providing the industrial know-how for long-term carbon storage. Carbon dioxide flooding in both China and the United States began in the 1960s. While the United States produces about 300,000 barrels of EOR oil per day, China's EOR efforts still face significant hurdles. This paper presents a compilation and brief review of CO_2-EOR data, some of it previously unpublished, from the three major Chinese oil companies (China National Petroleum Corporation, Sinopec, and Yanchang Petroleum Company) and one private company (Dunhua) that presently maintain pilot CO_2-EOR floods. The authors have visited several of the projects discussed in the paper and some observations from these visits are included. China's EOR projects generally produce from deep, tight, largely continental clastic reservoirs requiring hydraulic fracturing to create flow paths. There are no separation and recycle facilities—necessary to contain CO_2 in the system– and there are presently no supercritical pipelines for CO_2 supply. Several CO_2-EOR projects have established monitoring and storage pilot projects but the absence of recycle means determination of net storage is not possible. China's projects could benefit from improved reservoir selection, new CO_2 monitoring tools and operating strategies, expanded front-end investments in CO_2 infrastructure such as pipelines and modern surface separation and recycling facilities that will serve to reutilize and store CO_2.

1. Introduction

Carbon capture, utilization and storage (CCUS) could be an important carbon mitigation tool toward meeting China's decarbonization goals; China's 13th 5-year plan sets out a goal of reducing CO_2 emissions per unit of GDP by 18 % by 2020 against a 2015 baseline. China, with the world's largest CO_2 emissions, rich coal reserves and waning oil production, has undertaken an effort to develop CO_2-EOR utilization methods in its oilfields to both decrease carbon emissions while increasing oil production. Since its 11th Five Year Plan China has invested approximately 3 billion Chinese Yuan (CNY) (approximately one half billion U.S. dollars) in CCUS development, including 14 pilot capture and storage projects. In addition, China has committed to decrease its carbon intensity by 60–65 % of 2005 levels by 2030 (Asia Development Bank, 2017). This paper attempts to fill a gap in available CO_2-EOR data published in English-based scientific publications by providing an overview of known CO_2 flooding projects in China. We briefly compare the current status of CO_2-EOR with selected projects in the U.S., and make recommendations toward advancement of CO_2-EOR storage in China. We have collected information from a wide variety of sources including publications only available in Chinese language, workshops and conferences, and from site visits by the authors, generously hosted by several oilfield production companies (Yanchang Jingbian, CNPC Junggar, Sinopec Shengli, CNPC Jiyuan) between 2014 and 2018. This is the first English language review of CO_2-EOR projects across China we are aware of and presents information that may be helpful in understanding the potential for CO_2-EOR to play a role in emissions mitigation in China.

China's coal-fired power and coal-based industrial petrochemicals sectors continue to expand, with attendant increases in carbon dioxide (CO_2) emissions. Modern CO_2-EOR processes can play a role in mitigating these emissions, providing a net reduction in carbon emissions from captured sources while improving hydrocarbon production and revitalizing depleted oilfields (IEA, 2015). With CO_2-EOR, emissions from these sources can be reduced, while producing oil that has a lower carbon intensity/footprint than average (Cooney et al., 2015).

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Moreover, CO_2-EOR can help build China's know-how for future saline sequestration of captured CO_2. Because of the typically high price of CO_2, EOR also can provide a revenue stream back to the capture source necessary to offset the cost of carbon capture technology and build out transport and storage options (MacDowell et al., 2017.) Outside of electric power generation, CCUS may be the only technology that can reduce the process−CO_2 emissions from industries such as cement, iron, steel, petrochemicals, and China's coal-to-chemicals industry.

China, the United States and Canada were early developers of CO_2-EOR. More recently, CO_2-EOR projects are under development in Brazil, Norway, Trinidad, Turkey, Saudi Arabia and the United Arab Emirates (Kuuskraa and Wallace, 2014). These countries have recognized CO_2-EOR storage as an important step toward carbon reductions from industrial and energy sources through large-scale carbon capture projects. China's total annual CO_2 emissions were 10 Gt (billion tonnes) in 2018 (Global Carbon Atlas, 2018) up from 3.1 Gt in 2000 (EIA, 2016). In comparison, the total U.S. CO_2 emissions were 4.8 Gt in 2016, down from 5.7 Gt in 2000. Recognizing the challenge China faces in slowing and eventually reversing the rapid growth of CO_2 emissions, it has established a cap-and-trade program, which has set provincial limits to reduce the carbon intensity for industry (IEA, 2015). In comparison, the U.S. has no national carbon cap-and-trade program, yet a number of states have set goals to become carbon-free in the next several decades (Plumer, 2019). In establishing the 45Q tax credit program, the U.S. Congress recognized the importance of CCUS as a tool for reducing fuel carbon intensity. Similarly, the Chinese government sees CCUS as a tool for both domestic energy security and for helping lower carbon intensities from fossil combustion sources. In response, NOCs (national oil companies) have prioritized EOR development, including setting up EOR research and demonstration programs that have resulted in pilot projects a across China.

Carbon dioxide enhanced oil recovery, the technological basis for CCUS, is taking on an active role in first movers in sequestering captured CO_2 in depleted oilfields in the U.S. where approximately 68 million tonnes (Mt) of CO_2 (NETL, 2015) are currently transported to EOR sites via over 8,400 km (PSMA, 2020) of dedicated CO_2 pipelines annually. Motivating CCUS projects in depleted oilfields are recently adopted U.S. Internal Revenue Service 45Q CO_2 utilization incentives which can be accessed by CO_2-EOR operators willing to undertake monitoring, verification and accounting activities. Methods have been developed for optimization of CO_2-EOR-storage depending upon whether the investment objective is maximization of oil production or CO_2 storage (Ettehadtavakkol et al., 2014; Ampomah et al., 2017).

CCUS also represents an opportunity for China's oil companies to build captured CO_2 supply to feed actively expanding EOR activities in light of declining conventional oil production while storing CO_2.

Both the United States and China have utilized CO_2 for tertiary recovery in depleted oil fields since the 1970s. Yet, CO_2 flooding has been met with far more success in the U.S. EOR projects in the U.S. are well known and described in the literature (Meyer, 2008; Kuuskraa and Wallace, 2014.) However, details of China's CO_2-EOR projects and prospects remain largely unpublished in the West. China's CO_2-EOR potential has been preliminarily assessed by Advanced Resources International (ARI) which estimated in 2011 that 3,883 Mt of captured industrial CO_2 would produce 14,000 million incremental barrels of oil (approximately 1867 Mt of oil) by CO_2-EOR (Godec, 2011.)[i]

China's complex petroleum geology occurs in several depositional/tectonic basins, typically Mesozoic-Cenozoic in age which have been formed by continental sedimentary tectonic processes (Petroleum Geology of China, 1992). As a result, most of China's existing major oilfields generally lack the thick, productive marine sedimentary shale-sandstone sequences found in the U.S. marine sedimentary complexes. China's Sichuan Basin, in central China, is China's principal marine sedimentary basin, with natural gas production and development of unconventional shale gas resources, but the Sichuan Basin lacks large oil fields with CO_2-EOR potential. Marine geologic facies exist in the thick clastic sequences of the Junggar and Tarim Basins of the Xinjiang Autonomous Region in western China, but continental facies dominate and are produced in CNPC's Xinjiang Oilfield the Junggar Oilfields (CPGEC, 1991; Li and Lu, 2002). There have been several CO_2 injection EOR pilots these two basins as described below. One of the most productive basins in China is in the Shandong Province in eastern China, which operated by Sinopec, the location of its Shengli Oilfield—one of China's largest– and the site of Sinopec's Gaoqing-89 EOR project. In northeast China lies the Songliao Basin in Heilongjiang and Jilin Provinces. The Daqing and Jilin Oilfields in this basin have played an important role in EOR development, as described later in this paper. One of the most important petroleum-bearing basins in China is the Ordos Basin in north Central China (Li et al., 2014), home to China's largest oilfield, the Changqing Oilfield with CNPC's Jiyuan block CO_2-EOR project. The south China Sea and the East China Bohai Bay each produce about 200,000 bbls (27 Kt) per day and may, in the future, be reexamined for CO_2 flooding (Guo et al., 2018).

2. History of geologic CO_2 Management / CO_2-EOR in the U.S. and China

In 2013, China surpassed the U.S. as the largest net importer of petroleum in the world (EIA, 2018). This underlines the potential importance of enhanced recovery to China's domestic energy security. China's demand growth in 2014 accounted for 43 % of the world's growth in oil consumption, producing approximately 4 MMbbls (533 Kt) per day in 2016 while consuming a total of 12 MMbbls (1.6 Mt) per day. This compares with U.S. production of over 11 MMbbls (1.5 Mt) per day (including natural gas liquids) and consumption of approximately 20 MMbbls (267 Kt) per day in 2018.

CO_2-EOR methods developed over the past half-century provide the underlying technical basis for injection and storage of captured CO_2 in geologic formations. Experimental CO_2 injections began over a half century ago in the early 1960s in both the U.S. and China. The history of CO_2-EOR in West Texas is well known. In the U.S., CO_2 injections were initiated in 1954 in the Mead Strawn Oilfield, followed by commercial-scale CO_2 flooding in 1972 at the SACROC field in Texas. To date, over 1 Gt of CO_2 has been injected for the purpose of enhanced oil production, however much of the injected CO_2 is mined natural CO_2 (Hill et al., 2013). Today, approximately 83 % of CO_2 utilized in the U.S. is natural, the remaining 17 % captured from industrial processes. And although modern EOR processes result in unrecoverable, trapped CO_2, the injected captured CO_2 lacking monitoring, verification and accounting, and would not be considered to be stored.

Three of China's four largest petroleum companies have undertaken CO_2 flooding pilots: 1) PetroChina, China National Petroleum Corporation (or CNPC) the largest national oil company (NOC), comprising 54 % of all oil production in China in 2016; 2) Sinopec–China Petroleum and Chemical Corporation (the second largest NOC); and 3) Shaanxi Yanchang Petroleum (a provincial company and the 4th largest oil company in China). Despite the CO_2 injection efforts of the three companies, thermal and chemical EOR methods dominate the China's tertiary oil production (Guo et. al. (2018). The remaining petroleum company of China's top four, China National Offshore Oil Company (CNOOC), has considered the possibilities for EOR on its offshore rigs in the South China Sea, but has yet to undertake injection testing that we are aware of.

CO_2 flooding and enhanced oil recovery experiments began in 1963 in China National Petroleum Corporation's (CNPC) Daqing Oilfield, in the Heilongjiang Province in Northeast China. Results were favorable,

[i] Conversion of bbl to metric tonnes is based on oil gravity at PetroChina's Daqing oilfield 0.83−0.86 gm/cc (mean: 0.845 gm/cc) specific gravity ∼ 7.46 or ∼7.5 bbl/tonne. Source of gravity figure: http://www.searchanddiscovery.com/documents/2018/70350liu/ndx_liu.pdf.

suggesting that CO_2 flooding could increase production by 10 percent of original oil in place (OOIP) (EIA, 2018). From 1990–1995, water alternating gas (WAG) (CO_2) injections were undertaken in Daqing, resulting in a 6 percent increase in production followed by further CO_2 injections in the Sinopec Jiangsu Oilfield, Jiangsu Province in Southern China in 1998 (Liu et al., 2002); SINOPEC, 2016). In 1999 1500 tonnes of CO_2 were injected in the Xinli Oilfield in Jilin Province. Later, in 2006, a CO_2 WAG flooding pilot was undertaken in the Caoshe oilfield in Jiangsu Province in the Subei Basin of Eastern China. More recently in 2008, CO_2 flooding pilots were initiated by CNPC in additional production blocks in Daqing oilfield with reported success. Since this time, over the past decade, a number of CO_2-EOR projects, many with the secondary objective of storage, have been initiated across China, as described below. Wei et al. (2015) model results suggest that several billions of tonnes of CO_2 may be economically stored in the process of producing 7.7 Bbbl (1.0 Gt) of incremental crude through CO_2-EOR under presumed techno-economic conditions.

3. Description of CO_2 EOR Projects in China

3.1. Introduction

Fig. 1 is a map of EOR projects across China. A reported 34 EOR projects of various kinds have been conducted in China, but while momentum has begun to build toward larger CO_2 flooding operations, China's CO_2 flood volumes have yet to expand its production significantly beyond its pilot tests. One impediment to enhanced recovery development is that China's depleted reservoirs are challenged by deep, tight indurated fluvial clastic rock deposited in lacustrine basins that require fracture stimulation to increase permeability in order to make commercial production possible. Enhanced oil recovery from all enhanced recovery methods (including water, chemicals, steam, N_2 and CO_2) accounted for 18 percent of China's production in 2016 (Guo et. al., 2018). Moreover, the scarcity of water in China's arid oilfields have limited some EOR operators' abilities to waterflood and has motivated research and development on CO_2 utilization given the accessibility of relatively pure CO_2 from China's industrial sources. China is presently evaluating enhanced water recovery methods in combination with CO_2 injections, a saline geologic sequestration method (non-oil recovery) which could, in combination with reverse osmosis, provide the potential to increase water resources in China's coal chemical industry and petroleum basins (Li et al., 2019). While the U.S. oil production has soared due to shale oil resource development, far surpassing CO_2-EOR, China's unconventional oil development has proven more challenging than expected, despite the initial optimistic estimates of its potential in China (EIA, 2015). Still, these same unconventional oil and gas drilling and reservoir stimulation techniques, such as horizontal drilling and hydraulic fracturing are being adapted to the tight sandstone CO_2-EOR prospects, largely continental sandstone reservoirs in China's interior fault bound basins, such as the Changqing, Jingbian and other oilfields.

None of China's EOR projects inject CO_2 in the supercritical state, which is a ubiquitous process for enhancing oil-CO_2 miscibility in U.S.

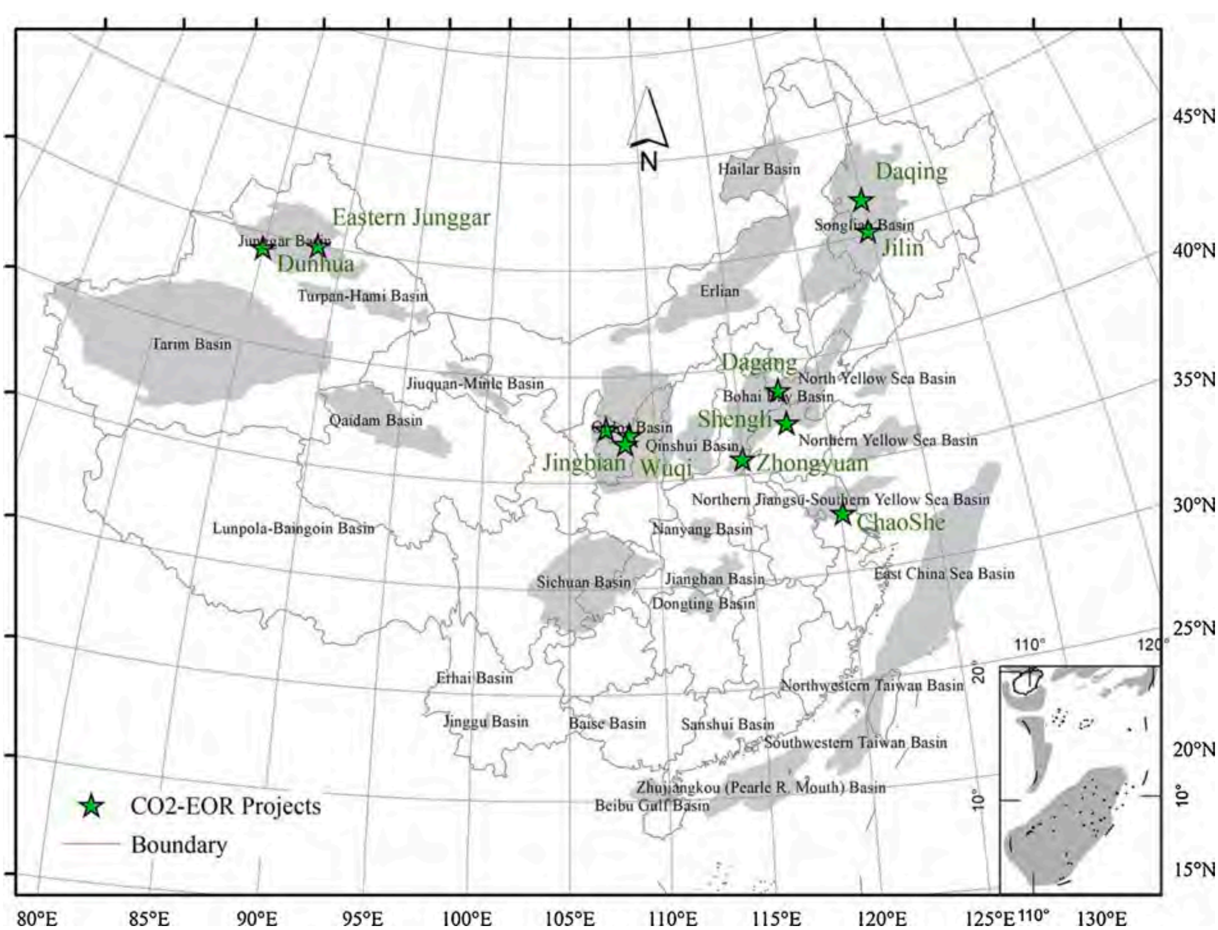

Fig. 1. China's sedimentary depositional basins (basins shaded, provinces outlined) and CO_2 flooding projects discussed in this paper. China's petroleum basins hosting CO_2-EOR projects are the: the Songliao Basin in far northeast China, with CNPC's Daqing and Jilin projects; The Bohai Basin occupying the region of the Bohai Sea East and South of Beijing including CNPC's Dadang Oilfield in Tianjin, Sinopec's Shengli and Zhongyuan Oilfields; north central China's Ordos Basin, hosting CNPC's Changqing Oilfield (China's largest) and Shaanxi Yanchang Petroleum's Jingbian and Wuxi fields; the Southern Yellow Sea Basin with Sinopec Jiangsu Huadong field; and finally the Junggar Basin in Xinjiang Autonomous Province, far western China.

CO_2-EOR systems. Instead all projects inject liquid or gas-phase CO_2, which may transition to the supercritical phase at depths below approximately 800−900 m. While most is delivered by truck, several short gas or liquid-phase pipelines are in operation in China (Jilin, Caoshe and Shengli) that terminate at and feed small CO_2 liquification plants prior to injection (Zhang et al. (2017). China's companies have yet to construct supercritical pipelines, modern surface CO_2 separation and recycle facilities. However, pilot CO_2 gas-phase CO_2 recycling operations have been conducted at CNPC's Jilin oilfield and tested at Sinopec's Shengli Gaoqing-89 block project as reported to us during a field visit in 2017. Construction of modern separation recycle and control facilities, critical to contain and store CO_2 in the EOR system and for efficient utilization of CO_2, reportedly await greater CO_2 flooding success and higher oil prices.

Although supercritical CO_2 pipeline systems have yet to be built in China, there are several small or medium scale liquid or gas-phase pipelines in China. One of China's academic laboratories, at Dalian University of Technology in the city of Dalian, northeast China, maintains a supercritical CO_2 pipeline laboratory where laboratory-scale crack propagation and plume dispersion has been tested (Yan et al., 2018). The University's 0.25 km field test pipeline, which we visited in 2017 has been constructed in the city of Anbo, further north in the Liaoning Province, where the short section of doubly-terminated test pipeline containing liquid CO_2 is wrapped in heating coils to achieve a supercritical state. The test pipeline is the site of China's larger scale sand and air leak dispersion experiments.

Today, CNPC, Sinopec and Yanchang Company all operate CO_2-EOR pilot projects fed by CO_2 from capture projects (Guo et al., 2018). Several of these projects have undertaken pre-FEED or FEED studies toward becoming full-chain commercial-scale CCUS projects, by building CO_2 pipeline supply from captured industrial sources and electric generating units, such as the Sinopec Shengli project, Shaanxi Yanchang Yulin/Jingbian project, as well as CNPC Jilin and Changqing (Cheng et al., 2017). The projects apparently await higher oil prices and more favorable economic conditions.

Wei et al. (2015) examined the economics of EOR for 296 of China's onshore oil fields, representing approximately 70 percent of China's mature fields. The analysis, based on proved OOIP, found that China has the technical potential for CO_2-EOR to recover approximately 7.7 Bbbls (1.0 Gt), with the attendant capability of storing in the process 2.2 Gt of CO_2. Their oil price sensitivity study suggests that oil production is critically dependent on crude oil and CO_2 cost, project lifetime and tax policies and that the barriers to full commercialization to be largely cost-related.

The following provides a brief summary of known CO_2 flooding projects in China.

3.2. Description of China National Petroleum Company (PetroChina) CO_2-EOR Projects

The China National Petroleum Company CNPC is undertaking the following CO_2 flooding projects in several of its approximately dozen petroleum provinces (CNPC, 2014a). CNPC CO_2-EOR field data is summarized in Table 1.

Table 1
EOR field data summary, CNPC (PetroChina). (Shen and Dou, (2016); Guo et al (2018), Ren et. al. (2016); Peng (2010); CNPC (2014b), 2018; Chi et al. (2013); Cheng et al. (2017); Cheng (2018); Li and Lu (2002); Zhang et al. (2018); Rungan (2018), Wang et al. (2014).

Province	Oil Field Production Block	CO_2 Source/ Injected tonnes to 2016	Geologic Description	Miscibility	Injection depth (m)	Porosity (%)	Permeability (mD)	Injectors/ Producers	References
Jilin	Block 228	Liquified natural gas separation, Changshen gas field/no data	no data	immiscible	1500	12%	<1mD	1/no data	Shen and Dou (2016)
Jilin	H 87−2	Liquified natural gas separation, Changshen gas field/no data	no data	immiscible	2300	10 %	<1 mD	1/no data	Shen and Dou (2016)
Jilin	Jilin HEI-59	Liquified CO_2 natural gas separation, Changshen gas field/ 341,000	Tight fluvial sandstone	immiscible	2445	11%	3mD	5 or 6/24	Zhang et al (2015); Shen and Dou (2016); Ren et al (2016). Peng (2010); CNPC (2018).
Jilin	H-79N	Liquified natural gas separation/ Changshen gas field/no data	Sandstone Q1	immiscible	2400−2450	12−16	5−10 mD	18/63	Shen and Dou (2016); Zhang et. al. (2018); Guo et al (2018).
Jilin	H-79B	Liquified natural gas separation/ Changshen gas field/no data	Sandstone Q1	immiscible?	2450	13	5 mD	10/19	Shen and Dou (2016); Zhang et. al. (2018); Gou et.al. (2018).
Heilongjiang	Daqing B-14	liquid industrial CO_2 trucked/no data	Tight fluvial sandstone	immiscible	1730	14	1mD	10/no data	Shen and Dou (2016)
Heilongjiang	Daqing Fang-48 pilot block/ Fuyu reservoir	liquid industrial CO_2 trucked/no data	Sandstone	immiscible	1880 (2003) /1742 (2007)	15	1 mD	1 (2003) 15 (2007)/5	Chi et al. (2013); Guo et al. (2018)
Heilongjiang	Daqing S101	liquid industrial CO_2 trucked/ no data	Sandstone F1	immiscible	2120	11	1	8/no data	Shen and Dou (2016)
Shaanxi	Changqing/ Jiyuan Block	liquid industrial CO_2 trucked/ 376,000 tonnes	Tight fluvial sandstone and delta fan	miscible	1000−1350. 2750 m	7%	50−254	Sep-37	Cheng et al (2017); Cheng (2018); Rungan (2018); CNPC, 2014b., Wang et al (2014).

3.2.1. Daqing Oilfield

Heilongjiang Province, Songliao Basin, NE China. Daqing Oilfield is a supergiant oilfield comprised of Mesozoic continental sandstones. Production at Daqing began with the drilling of the Songji No. 3 well in 1959 (Duey, 2015). Long considered one of CNPC's more important producing oilfields and is where China's first CO_2 tests took place as a method to slow the steady decline of the oilfield. Daqing is one of China's two largest oilfields (the other Changqing). At 41.67 Mt per year (approximately 305 MMbbls (41 Mt) annually / 0.84 MMbbls (110 Kt) daily) (Xinhua, 2019), Daqing's oil production constituted roughly 17 % of China's 4.8 MMbbls (640 Kt)of daily oil production in 2018 (EIA, 2019). Notably, this is a similar production rate as the 300,000 annual bbls (40 Kt) of CO_2-EOR produced oil in the U.S. in 2014 (Kuuskraa, 2014.) As noted above, initial research and pilot injection efforts began in 1963. Results were optimistic and suggested that CO_2 flooding could increase production by 10 percent (Wu et al., 2011). From 1990–1995, water alternating gas (WAG) (CO_2) injections were undertaken in Daqing, resulting in a 6 percent increase in production. Daqing has widely implemented water flooding across the oilfield reportedly with over 9000 injector wells to offset production declines. With waterflooding also in decline, efforts were made to improve production by CO_2 flooding which was reinitiated in 1999. The CO_2 flooding is immiscible based on data from the B-14 well which indicates a very tight (1 mD) discontinuous continental channeled sandstone at a supercritical injection depth of 1730 m. with 13 % porosity. In 2009 there were 10 CO_2 injector wells, with a reported 200 Kt of liquid CO_2 injected per year supplied by truck from nearby industrial sources (Shen and Dou, 2016).

3.2.2. Jilin Oilfield

Jilin Province, Songliao Basin, NE China. The Jilin project is considered as the prototypical CO_2 flooding project in China and the site of CNPC's state-level "CCS-EOR Technology R&D Center and Demonstration Base" (CNPC, 2018). Commercial oil and gas production at the Jilin oilfield developed in the 1960s and CO_2 flooding was initiated in 2007 with the purpose of demonstrating the technical and economic feasibility of CO_2-EOR in tight reservoirs in China (Zhang et al., 2015). CNPC (2018) reports that CO_2 flooding in Jilin's Daqingzi oilfield is supplied by CO_2 separated at the Changling gas field (CO_2 concentration 22.5 %) approximately 50 km from the field, and transported by pipeline or truck (depending on source) a compression facility then injected as water-alternating-gas (WAG) (Peng, 2010). CNPC (2018) reports that produced CO_2 is recycled and recompressed and reinjected. The quantity of available CO_2 is about 200 million cubic meters, and able to supply 45 well groups. Supplemental CO_2 is provided by coal-to-chemical facilities such as fertilizer and methanol plants. There is a gas separation facility that recycles gas-phase CO_2 which is then sent to the liquification facility. CNPC has been reportedly injecting up to 100,000 tonnes per annum (tpa) in 69 well "groups" into the Jilin oilfield since 2009. Tang et al. (2014) report that as of 2011 oil production 119,000 tonnes (about 8.7 mmbbl) of oil were produced utilizing about 167,000 tonnes of CO_2. A separation plant was constructed in Jilin designed to separate 200,000 tpa of CO_2 (Tang et al., 2014) with reported 270,000 tonnes "safely" stored as of the end of 2012. A total of 341,000* tonnes had been injected as of 2016 (Shen and Dou, 2016; CNPC (2018), apparently inconsistent with earlier estimates, reports that as of April 2017, 1.1 Mt of CO_2 had been stored, "at a rate of 96 % "with an accompanying increase in well productivity by 13 % as compared to the response from water flooding. Accompanying the injection is a carbon storage monitoring program estimating that 80 % of the injected had been stored with the remaining 20 % breakthrough into production wells (Zhang et al., 2015). A 1 Mt pipeline has been reportedly designed in a CNPC pre-FEED study with the intent of upgrading the project to commercial scale.

The principal flooding project is being conducted in the HEI-59 production block (Tang et al. (2014) in a block-faulted complex. In 2007, tertiary light oil (0.76 gm/cm^3) was reportedly being produced in the HEI-59 area from the Mesozoic age Qing-1 Formation from intervals 11−28 m. in thickness (Zhang et al., 2015). The Qing-1 at the reservoir depth of 2000−2400 m. is a tight continental interbedded sandstone and mud, producing with 6 injectors and 25 producers, at a spacing of 250−300 m. with a permeability of 4 mD, and porosity of 13 % and a bottom hole pressure of 28−32 MPa at approximately 100 ℃, such that the injected liquid CO_2 reaches supercritical condition. To stimulate the reservoir, hydraulic fracturing has been undertaken at production wells. Still, the incremental recovery rate was 5% percent prior to CO_2 injection (Zhang et al., 2015) As of 2016, there were a reported 6 injectors and 24 producers in the Qing-1 Formation arranged in a five-spot pattern. The flood is miscible (Peng, 2010) (MMP 22 MPa, with an original reservoir pressure 24 MPa, progressively decreased to 18 MPa from production), slim tube minimum miscibility pressure of 23 MPa (Zhang et al., 2017a,b). The injectate is typically water-alternating-gas (WAG) with liquid-phase CO_2 generated onsite from gas-phase CO_2 generated at the Changshan-4 well and pipelined from a natural gas separation plant (Zhang et al., 2015) and injected at a rate of 30−50 tonnes per day (Zhang et al., 2015).

Future CO_2-EOR efforts are being considered for the HEI-79 block of the Jilin oilfield (Zhang et al., 2015; Peng, 2010). CNPC engineers are also presently in the process of applying the learning and technology from the Jilin Oilfield toward doubling the CO_2 flooding project at Changqing Oilfield Jiyuan Block in the Ordos basin spanning the Ningxia and Shaanxi Provinces in northern China (Hill, Wei, site visit 2018).

3.2.3. Changqing Oilfield

The third major CO_2-EOR effort of CNPC is its Changqing Oilfield Jiyuan Block project, located in the Shaanxi and Ningxia Provinces, North-Central China (CNPC, 2018). (Fig. 2) Changqing, situated in the Ordos Basin, is China's third largest and perhaps most rapidly growing EOR project, also with conventional production reportedly in decline, and like Daqing, active waterflooding in an effort to rebuild production (Wang et al., 2014). One of CNPC's most recent CO_2 flooding efforts, CO_2 injections have been underway since the early 2000′s in the Huang-3 Jiyuan Block (Cheng et al., 2017). There, CNPC is actively injecting a steady supply of 60 tpd /50,000 tpa of liquid CO_2, a 0.5 HCPV flood, transported by 3 trucks daily and buffered by several large liquid CO_2 storage tanks at the site. (Hill, Wei, site visit 2018). CO_2 produced with the oil is not recovered nor recycled at the site. The CO_2 is sourced from industrial processes in the nearby NingDong industrial area in East Ningxia Autonomous Region which is known for its coal to chemicals industry and concentrated industrial CO_2 emissions. The Jiyuan Block produces out of the Triassic Yanchang Formation, a highly fractured continental sandstone at a depth of 3,000 m. The low-pressured

Fig. 2. CNPC Changqing Oilfield Jiyuan Block EOR project in the Ordos Basin, Shaanxi Province. (N. Wei, 2018).

reservoir is tight, low 7 percent porosity with sub-Millidarcy (air) permeability (8 mD by in-situ electronic well logging). Hydraulic fracture stimulation has been used to increase permeability to 7 mD at the field. In fall 2018, when the authors visited Jiyuan, CO_2 was being injected in 9 wells with 36 producers arranged in 9-spot patterns. Cheng et al. (2017) reports a total of approximately 376,000 tonnes had been injected with a commensurate 315,000 tonnes of oil production (approximately 42,000 bbl). Flooding is miscible with a minimum miscibility pressure (MMP) of 19.8 MPa, and a formation pressure of 19.7 MPa. Reported recovery was estimated at about 20 % relative to 10 % recovery from water flooding. Cheng et. al. (2017) also report a sequestration rate of 73 percent, but the basis for this determination is unclear. CNPC plans to double the size of the facility from 50,000 tpa to 100,000 tpa in 2019, with engineering provided by the CNPC Jilin Oilfield Company (Hill, Wei, site visit, i 2018). CNPC has studied future large-scale expansion at the Jiyuan block with a 1 Mtpa "Ningdong" pipeline. CNPC engineering suggests that 5 CO_2 pipelines could serve 80 percent of the CNPC Changqing Oilfield wells (COACH, 2009).

3.2.4. Junggar Zhundong Oilfield

Junggar Basin, Xinjiang Uyghur Autonomous Region, Western China. The Junggar basin, northeast of Xinjiang's capital city, Urumqi, is characterized by intercalated continental and marine sedimentary rocks. Pilot scale CO_2 injections have been undertaken in its ultra-heavy oil FengChang field, for the purpose of enhancing its production (Hill, site visit, 2015). Junggar Zhundong (Eastern Junggar) remains under consideration for future flooding projects and is the site of the independent oil company, Dunhua project (described below).

3.2.5. Liaohe Oilfield, Liaoning Province

Liaohe Oilfield in the northern China province of Liaoning along the Bohai Bay northeast of Beijing, is known for its tight sandstone and ultra-heavy oil. A range of enhanced recovery methods have been employed, including horizontal well sidetracks, at depths of 500−1700 m. To mobilize the oil, methods have included steam, chemical flooding, nitrogen and 13–14 % (by volume) CO_2 flue gas (Jin et al., 2018). Researchers have noted that Liaohe is unsuitable field for conventional waterflooding or CO_2-EOR

because of the low API gravity of the oil. However, efforts have utilized chemical flooding methods as well as liquid phase immiscible CO_2 in combination with steam injection and hydraulic fracturing which has improved sweep efficiency and production rate by 12–13 %.

3.2.6. Dagang Oilfield

The Dagang Oilfield is located in the Bohai Bay Basin East of Beijing near Tianjin. Dagang was identified as a potential EOR receptor site for trucked liquid CO_2 captured at the China-U.S. Clean Energy Research Center (CERC) GreenGen project (Yang et al., 2016). The Ordovician, Mesozoic, Paleogene and Neogene age, clastic fluvial reservoirs are contained within small fault blocks containing low-API gravity, high viscosity oils. Yang et al. (2016) also suggests that there is CO_2-EOR potential in highly fractured 9 sub-fields of Dagang, with the Banqiao field identified as most suitable (based on the distance from the GreenGen capture site near Tianjin.) In 2007, a small injection pilot was undertaken at Dagang. The 1.5-year pilot test was conducted using natural gas from a nearby gas field with a 20 % CO_2 content. The gas and injected into a single well in the Kongdian reservoir of the Dagang oilfield complex. It is reported that oil production from the well was increased from 14 to 68 bbl (2−9 t) per day.

3.3. Description of Sinopec CO_2-EOR Projects

Sinopec EOR field data are summarized in Table 2.

3.3.1. Shengli Zhenglizhuang Oilfield, Gaoqing-89 Production Block

Gaoqing 89 production block is located in Shandong Province, Bohai Basin, Eastern China. Shengli Oilfield is China's second largest and began producing oil in the mid-1960s and produced about 557,000 bbl of crude per day in 2014. The Gaoqing-89 (Gao-89) production block is the site of Sinopec's most ambitious EOR project, a project with potential to be China's first full-chain carbon capture utilization and storage (CCUS) operation. The Shengli Oilfield is one of China's largest, situated in a heavily industrialized high CO_2 emissions region in the Shandong Province. The Shengli Oilfield is powered by a large coal-fired power plant in Shandong's DongYing City which was retrofitted with Sinopec proprietary amine–based carbon capture technology on a 25 MW slipstream from Unit 1. The company has done pre-FEED studies on two CO_2 pipelines from the Dongying area to the Gao-89 block. The first would be a supercritical CO_2 pipeline from a planned capture-ready third unit the power plant. The second would be a gas-phase CO_2 pipeline from the nearby QiLu refinery located in the Sinopec Shandong's large petrochemical complex. Gao-89 block is approximately 100 km distant from these CO_2 sources. As of 2020 Sinopec was studying scale-up to a 2 Mtpa CO_2 system (Lu, 2020, pers. comm.).

The small but commercial Gao-89 EOR site (See Table 2 and Fig. 3) has undergone active flooding since 2007 utilizing CO_2 liquefied from a pipeline carrying naturally-sourced CO_2 from the Huaguo gas reservoir in combination with liquid CO_2 delivered by trucks from the Dongying petrochemical area (Ma et al., 2018). This CO_2 is injected to a depth of 2, 350−3,400 m. into the Shahejie Formation a Cretaceous-age tight

Table 2
EOR field data summary, Sinopec. (Shen and Dou, 2016; Guo et al., 2018; Jiang, 2019; Li and Lu, 2002, Zhang and Wang (2010)).

Province	Oil Field Production Block	CO_2 Source/Injected to 2016	Geologic Description	Miscibility	Injection depth (m)	Porosity (%)	Permeability (mD)	Injectors/ Producers	References
Shandong	Shengli Gao-89	Trucked liquid and pipelined naturally-sourced gas/ liquidified CO_2 from DongYing power station and QiLu CTX area/240,000	Fluvial sandstone	Miscible	2950 (2800~3200)	13 %	0.1−24 (5) mD	5/15	Dou et al (2016); Guo et al (2018); Jiang (2019); Ma et al. (2018).
Henan	Zhongyuan	Trucked from Sinopec Zhongyuan Oilfield Company Petrochemical Plant where 20,000 tpa installed in 2016*	Fluvial sandstone	miscible	3800−4400	18−28%	123−690 mD	22/38	Dou et al (2016); Guo et al (2018); Jiang, (2019) ; u et al (2016a)
Jiangsu	CaoShe Fu-14	Barge and truck, Natural and captured industrial/ conflicting data	Fluvial sandstone	Miscible	[2090] & 2800−3250	16−23%	[854] 24−114 mD (241)	4/2	Guo et al (2018); Shen and Dou. (2016); Zhang and Wang (2010).
Jiangsu	Huadong YYT JL	Naturally sourced from Huang Qiao CO_2 gas field/no data	Fluvial sandstone	Miscible	2300	12%	5−10 mD	43/117	Shen, P., Dou, H. (2016). Fan Zhenning (2017)

Fig. 3. Sinopec Gao-89 Block CO_2 injection facility. (Photo: Ning Wei, 2014).

fluvial sandstone reservoir with a permeability of 0.1–24 mD and an average of 5 mD, and an average porosity of 13 % (range 5–18 % (Shen and Dou, 2016; Ma et al., 2018). The Gao-89 block has an array of 14 producer wells combined with five injector wells in a geometric five-spot pattern (Hill, site visit, 2017). The miscible flood (minimum miscibility pressure 28 MPa, reservoir pressure 30 MPa) produces about 5 t of API 31 oil per day (appx 38 bbl/d). As of 2019, 260,000 tonnes of CO_2 had been injected into the Gao-89 block for the purposes of CO_2-EOR and storage (Lu, pers. comm., 2020).

The British Geological Survey, as a part of the China-EU CCS cooperative effort, COACH, from 2006 to 2009, estimated the total storage capacity of the Shengli oilfield, using a 2007 CSLF approach as 472 Mt accompanied by additional oil production of 23–112 Mt (140–683 mbbls) (COACH, 2009). The COACH study also identified rail, gas-phase pipeline and ship transport routes for captured CO_2 at the GreenGen capture site in Tianjin to Shengli.

3.3.2. Zhongyuan Oilfield, Bohai Basin

Zhongyuan Oilfield, Bohai Basin is located in the Dongpu Depression, Henan Province, Eastern China. Sinopec initiated a pilot injection project at the Zhongyuan oilfield in 2002 with the purpose of enhancing poor quality low permeability oilfields and carbon storage (Ma, 2017; Zhang et al., 2017b)), injecting 20,000 tonnes per year of liquid CO_2 captured at a nearby refinery, trucked to the oilfield. The completed capture project has a reported capacity of 100,000 tonnes of tailgas per year (Ma, 2017) captured by catalytic cracking. The project is a miscible flood injecting captured CO_2 trucked 50−170 km to the site from Kaifeng, Xinlianxin and Zhongyuan refining and chemical plants. Ma (2017) reports that the capture facilities have a capacity of 1 Mt. CO_2 is injected to the reservoir at a depth of 2450 m. which is characterized by a permeability of 2 mD and porosity of 12.7 % and a very high water cut of 90 %. A combined total of 113,800 tonnes had been injected from all available sources in the second half of 2015. Ma (2017) reports a current injection rate of 160,000 tpa for a total of approximately 0.5 Mt had been injected as of April 2017, 360,000 t in the Pucheng field. Total production resulting from these injections is approximately 100,000 tonnes (750,000 bbl) of oil.

3.3.3. Jiangsu Oilfield

The Sinopec Jiangsu Oilfield Caoshe block is located in the central coastal Jiangsu Province north of Shanghai (Sinopec, 2016). CO_2 flooding began in 2005 at a depth of 3,065 m., with a reported moderate permeability of 241 mD (Shen and Dou, 2016). Sinopec is investigating sourcing 50,000 tpa CO_2 from nearby ammonia plant and coal to hydrogen plants.

3.4. Description of Shaanxi Yanchang Petroleum Company's EOR projects

A summary of Yanchang Petroleum Company's EOR field data is summarized in Table 3. (Shen and Dou, 2016; Li and Lu, 2002; Gao, 2016a,b)

3.4.1. Jingbian and Wuqi EOR Storage Projects

The Shaanxi Yanchang Yulin-Jingbian Qiaojiawan EOR CCUS project is located in the Ordos Basin in northern China's interior near Inner Mongolia. The Ordos basin is characterized by late Jurassic continental sedimentation regimes during the Yanshan Orogeny. Yanchang's two EOR projects are situated on the east side of the Ordos Basin near Dongding, northeast of the CNPC Changqing oilfield (Yanchang Petroleum, 2015; Gao, 2016a, 2016b). Gao (2016a) estimates an EOR storage capacity of 0.5–1.0 Gt in its oilfields and additional billions of tonnes in deeper saline aquifers.

The Yanchang Yulin project, a collaborative of a number of domestic and international organizations, was recognized as a U.S.-China "Presidential Project" in 2015 by U.S. President Barack Obama and Chinese President Xi Jinping. The project promised to be China's first full-chain CCUS, but is currently on hold. Subsequent to the project's elevation as a Presidential Project, two Chinese CCUS projects received a total of U.S. $5.5 MM in support from the Asian development Bank (Asia Development Bank (ADB, 2017) including U.S. $4.3 millionMM to Yanchang to undertake engineering studies and planning. As a part of the process, cooperative pre-FEED studies by Sinopec's Pipeline Engineering group were completed for an 80 km pipeline to connect two capture sources in Yulin with the Jingbian and Wuqi EOR projects. In addition, planned expansion of the industrial capture facility at the Yulin Coal Chemical Company in the city of Yulin (Shaanxi), will have the future ability to provide 360,000 tonnes per year of CO_2 for EOR projects. A future third phase of expansion promises a potential of 1 Mtpa. Despite optimism, the 360,000 tonnes per year capture expansion project is on hold. Yanchang's EOR projects are located in the Inner Mongolia desert, and lack water resources, limiting water flooding. However industrial CO_2 is abundant in the region and the cost of capture is low (Wang et al., 2017a,b). In addition, the greater injectivity of CO_2 has been cited as an advantage over waterflooding in the arid region, as CO_2 injections have proven as much as double the injectivity of water. As result, Yanchang has prioritized research and development and field-testing of CO_2 technologies, including experimentation with CO_2 fracture stimulation.

The Yanchang Yulin EOR CCUS project (Fig. 4) is a near-miscible flood, underway since 2012 (Ma et al., 2017). Three truckloads of captured liquid-phase CO_2 per day, approximately 20 tonnes, are injected daily into the producing Chang-6 horizon of the Yanchang Formation (Hill, site visit, 2014). The Chang-6 consists of 105−150 m. of gray mudstones, siltstones and fine sandstone. The injection interval in the upper Triassic reservoir in the Qiaojiawan 203 well block is a shallow, tight, fractured arkosic deltaic channel sand at a depth of approximately 1600 m. (Yanchang Petroleum, 2015). The formation is under-pressured (13 MPa) and therefore the CO_2 flood is immiscible. The permeability of the Chang-6 is very low, typical of the basin, typically 1 mD, ranging from less than 1 mD to 12 mD, accompanied by an average 10 % (ranging from 8 to 13 %) porosity. A total of 720,000 tonnes of CO_2 had been injected as of 2016.

In 2014 Yanchang initiated a second CO_2 flooding project in the Ordos basin, the Wuqi Yougou block, with 5 injectors and 18 producers. Yanchang reported an injection rate of 19 tonnes per day and a pressure of 10.3 MPa. Numerical simulation indicated that CO_2 recovery be could be improved by relative to water flooding. Injected CO_2, transported at a cost of $2.58 per tonne, was captured at approximately U.S. $17.50 per tonne (Wang et al., 2017a,b).

Table 3
EOR field data summary, Shaanxi Yanchang Petroleum Company. Data Sources: Yanchang, (2015); Shen, P., Dou, H. (2016); Li, G., Lu, M., (2002), Gao, R. (2016a), Gao, R. (2016b) [16, 21, 30-31].

Province	Oil Field Production Block	CO_2 Source/Injected to 2016	Geologic Description	Miscibility	Injection depth (m)	Porosity (%)	Permeability (mD)	Injectors/ Producers	References
Shaanxi	Jingbian Qiaojiawan	Yulin Coal to chemical (methanol) Industrial CO_2) trucked from Yulin City to Jingbian oil field./ 60,000 t	Detrital river delta-lake sandstone	immiscible / near miscible	600−1900 (1600)	8−14% (12)	1−10 mD (1)	5 (16)/20	Yanchang, (2015); Shen and Dou, (2016). Gao, (2016a; Gao 2016b); Ma et. al. (2017)
Shaanxi	Wuqi	Yulin Coal to chemical (methanol) Industrial CO_2 trucked from Yulin City to Wuqi oil field./ 8125	Detrital river delta-lake sandstone	immiscible	1120−1420	17 %	91−475	4 injectors starting 2014; planned: 37/ 110	Yanchang, (2015); Gao (2016a),b)

Fig. 4. Yanchang Yulin-Jingbian CO_2-EOR pilot site, Jingbian, Shaanxi, China. (Ning Wei, 2013).

3.5. Description of Private Company EOR Projects

3.5.1. Dunhua Junggar EOR project

Dunhua is located in Xinjiang Autonomous Region, Junggar Basin. Dunhua is a Chinese domestic oilfield technical service company which expanded its operations by initiating an EOR project in 2015 in far western China's Junggar Basin. Dunhua is currently the only private Chinese company undertaking CO_2 flooding that we are aware of. Dunhua's project is utilizing 100,000 tpa of liquified CO_2 captured from the CNPC Karamay methanol plant, trucked southeast to the NW Junggar Oilfield (Yubin, 2018). Dunhua reported in 2018 that it was operating 2 injection wells accompanied by 6 producers. The company also said in 2018 that it planned to significantly expand its injections operations to 290,000 tonnes of CO_2, sourced from both CNPC and Sinopec industrial plants. Note, we have not verified if this increase was carried out. It is unclear whether this goal was achieved. Dunhua targets future expansions that would total 840,000 tonnes per year. And ultimately a 5 Mtpa Xinjiang CO_2-EOR project with recycling facilities in the northwest part of the Junggar Basin.

4. Comparative Features of U.S. and China Basins

In order to provide context for understanding China's CO_2-EOR projects, several CO_2 flooding operations in U.S. petroleum basins are briefly described below. U.S. CO_2 floods produce from both carbonate and clastic reservoirs. However, for comparison purposes, we briefly describe several CO_2 floods producing from clastic reservoirs in three basins. Table 4 provides data for five of the many CO_2-EOR projects in these basins as representative comparative examples. The data discussed below are sourced from the Oil and Gas Journal's Worldwide EOR Survey (2014).

4.1. Gulf Coast, Texas, Mississippi, Louisiana

The Gulf Coast reservoirs (for example, Denbury's Cranfield, Mississippi field listed in Table 4) are comprised of mostly Tertiary and Mesozoic marine-marginal fluvial and deltaic sandstones, such as the Cretaceous Tuscaloosa and Tertiary Frio Formations. They are sand-rich with Darcy-level permeabilities. The excellent injectivity is accompanied by an abundant natural and industrial CO_2 supply, available by supercritical pipeline that runs from Jackson dome (with several Gt of CO_2 trapped in a structural dome evaporite complex), Mississippi to

Table 4
Representative U.S. EOR field data in clastic reservoirs of the Gulf Coast, Rocky Mountains and the Permian Basin. Source: Worldwide EOR Survey (2014).

Basin, State/ Field	CO_2 source	Formation/ type	Miscible	Injection Depth (m.)	Porosity	Permeability –k Md	Injector/ Producer Wells
Denbury Gulf Coast, Mississippi, Cranfield	Pipeline supercritical CO_2 -Jackson Dome natural	Bailey/ marine sandstone	yes	3139	17 %	273	27/26
Four Corners Permian, Texas, North Ward Estes	Pipeline supercritical CO_2 McElmo Dome -natural	Yates/ marine sandstone	yes	793	16%	37	816/816
Fleur De Lis Rocky Mtn, Wyoming, Salt Creek	Pipeline supercritical CO_2 Shute Creek. Natural Gas separation	Wall Creek 1 nearshore marine sandstone	no/near	488	17 %	30	27/40
Occidental Rocky Mtn, Colorado Rangeley Weber	Pipeline supercritical CO_2 Shute Creek. Natural Gas separation	Weber aeolian to marine sandstone	yes	1829	12%	10	262/378
Merit Rocky Mtn, Wyoming, Lost Soldier	Pipeline supercritical CO_2 Shute Creek. Natural Gas separation	Tensleep aeolian to marine sandstone	yes	1524	7%	10	7/11

Houston Texas. Operators typically produce by direct CO_2 injection without the use of WAG. The young sediments with their high permeabilities probably do not represent useful analogs for China's EOR projects, with the exception of possible CNOOC offshore projects in the South China Sea in the sediments of the Pearl River Delta or in the Bohai Basin in north China. However, the pipelines and surface facilities are instructive as they allow for the injection of optimal slugs of CO_2 over the lifetime of projects.

4.2. Permian Basin, West Texas

The Permian basin is now the largest producing basin in the United States, is largely a carbonate platform, with reservoirs producing from the Permian San Andres Formation, accompanied by some shallow marine to continental sandstones (for example, the North Ward Estes field listed in Table 4). Occidental Petroleum's Denver Unit and Hobbs CO_2-EOR storage projects (see below) are situated in the carbonates of the San Andres. The carbonate producing intervals are characterized by wide range of permeabilities but typically in the range of 10–100 mD. Supercritical CO_2 delivered to the basin comes from natural sources (dome structure to the north in Colorado and New Mexico) and natural gas separation sources by pipeline. Kinder Morgan, a U.S. pipeline company and one of the earliest EOR developers of the Permian Basin, has injected over 175 million tonnes of CO_2 since 1972, producing 30,000 bbls/d. Four major CO_2 pipelines feed the Permian Basin transporting approximately 45 Mtpa of supercritical CO_2. As an example, Whiting North Ward Estes Field, with 15 mD permeability and 18 % porosity has a total of 816 injectors and 816 producers in line drive and 5-spot patterns produced by WAG methods. The Permian Basin's geology, with its carbonate reservoirs and secondary porosities may not provide a good analog for China's EOR projects, yet there is much that can be learned from its supercritical pipeline supply surface facilities and strategies. Residual oil zones have been discovered in the carbonates of the San Andres and thought to result from secondary porosity generated during the dolomitization process.

4.3. The Rocky Mountains, Wyoming, Montana

The Rocky Mountain EOR projects are characterized by Paleozoic and Mesozoic fluvial, marine and aeolian clastic rock sequences with lower permeability. Supercritical CO_2 comes from natural sources (dome structures) and natural gas separation. There are a range of reservoir conditions in the Rocky Mountains. The Salt Creek field is characterized by moderate to high porosities and permeabilities. The miscible Rangeley Weber field of Colorado (Table 4), and the near-miscible Paleozoic continental-marine transition sandstones of the Merit Lost Soldier Field in Wyoming (Table 4), which has been flooded for 30 years may represent closer analogs to China. The petrologic features of the Lost Soldier and Rangeley Weber fields are, perhaps, most similar to China's typical fields: 10 mD permeability, porosity of 7–13 %, API gravity of 35, and 1500−2100 m. depth. However, contributing to success in these projects are the volumes of pipelined supercritical CO_2 supply. Supercritical CO_2 from the Exxon Shute Creek natural gas separation plant floods the Lost Soldier field with a 60 % HCPV slug of water-alternating -gas (WAG) injections, recapturing produced CO_2 at its separation and recycle facility.

4.4. Discussion

China's reservoirs were formed in very different geologic and tectonic settings than U.S. reservoirs, in many ways accounting for why they are much more difficult to produce. In the U.S., petroleum basins were formed by marine and marine marginal sedimentation, typically more amenable to petroleum production. Moreover, many of the successful EOR fields in the U.S. are in carbonates, which also contain residual oil zones (ROZ) that will increase oil production and concomitant storage.

By comparison China's Mesozoic to Cenozoic age continental clastic sedimentary reservoirs are typically older and more consolidated. Its depositional basins are filled with sedimentary sequences from fluvial and lacustrine geologic settings, broadly affected by tectonics characterized by repeated post-depositional allochthonous terrane accretions and related deformation, burial, compaction, and related diagenesis. Some flooding prospects are quite deep, greater than 2000 m. As a result, many of China's projects are very tight, characterized by 0.1–10 mD permeability and difficult to flood, and, in turn, store CO_2. Because of the low permeability, the low API gravity (viscous) petroleum reservoirs need to be stimulated by hydraulic or CO_2 fracturing to improve flooding performance. For comparison, projects in the West Texas Permian Basin, as noted above, are characterized by permeabilities of a Darcy or greater, with West Texas intermediate API gravity crude oil, and are easily flooded with CO_2. Moreover, some of China's producing reservoirs are commonly under pressured and highly fractured, therefore difficult to achieve miscibility. In comparison, most of the tertiary production in the United States is from miscible CO_2 floods.

Another significant difference between U.S. and China's EOR projects is that all commercial-scale U.S. projects are all fed by supercritical-phase CO_2 pipelines, anchored at natural CO_2-producing dome structures, and are accompanied by sophisticated CO_2 separation and recycle facilities. While approximately 68 Mtpa of new CO_2 are pipelined for utilization in the U.S., much more CO_2 is utilized for flooding when the large volumes of recycled CO_2 are included. CO_2 -EOR production is currently about 300,000 bbls (40,000 t) per year. In contrast, China's projects are sourced by trucked liquid CO_2, rather than pipelined supercritical phase CO_2, and therefore may not achieve the ideal hydrocarbon pore volumes.

Alternatively, some of the very tight reservoirs in China may be more closely likened to the tight sand prospects in North Dakota and Wyoming such as the Bakken, which are produced by horizontal drilling and hydraulic fracturing. CO_2 stimulation has been considered, however investment would more likely go towards infield drilling or a conventional tertiary prospect with ample injectivity. However, because of China's choice of tight reservoirs for their projects, typically lacking easier prospects, tertiary flooding methods combined with horizontal drilling and hydraulic fracturing may be most effective in some of China's very tight sandstone fields.

5. Geologic Storage of CO_2 During EOR

5.1. North American CO_2 EOR-storage projects

Requisite for permanent storage in association with EOR are recycling systems that separate CO_2 for reinjection such that an injected tranche of CO_2 is progressively stored, less system losses. While EOR conducted with recycling systems alone is considered by some to be carbon storage (by virtue of physical, solution, residual trapping mechanisms), creditable storage of injected CO_2 must be proven up by monitoring, verification and accounting accounting for any CO_2 that could be lost through mechanisms such as leaky wells, seal failure, out of pattern/off-lease migration, outages that may require temporary releases, CO_2 blow-down and transfer, and system losses/emissions or other problems.

For example, in order to claim the U.S. IRS 45Q tax credit, the amount of CO_2 "…must be measured at the source of capture and verified…at the point of injection as a tertiary injectant in an enhanced oil or natural gas recovery project" (Internal Revenue Service, 2020). Recently proposed guidance for this tax credit requires monitoring, verification and accounting either under the Greenhouse Gas Reporting Program Subpart RR (EPA, 2010) or under International Organization for Standardization (ISO) 27,916 for CO_2-EOR storage. ISO 27916 standard uses mass balance accounting combined with a monitoring program and containment assurance. A second example is California's

Low Carbon Fuel Standard (LCFS). Companies seeking tax credits under the LCFS must follow it's "CCS Protocol" (California Air Resources Board, 2018) which, among other requirements, includes site selection, risk analysis, monitoring and accounting and post injection site care.

There are currently 5 projects in the United States with approved monitoring, reporting and verification plans (MRV plans) under the U.S. Greenhouse Gas Reporting Program (GHGRP) Subpart RR (EPA, 2010). Three plans are for EOR-storage (Occidental Petroleum's Denver Unit and Hobbs Field, and Core Energy's Northern Niagaran Pinnacle Reef). Archer Daniels Midland Illinois Industrial Carbon Capture and Sequestration Project's MRV plan is for dedicated saline storage in combination with an Underground Injection Control Program (UIC) Class VI permit. ExxonMobil's Shute Creek MRV 2019 revised plan covers 3 wells, all permitted under UIC Class II, for which the stated primary purpose is disposal of acid gas and other components of natural gas production at the site, with a secondary purpose of sequestration (EPA, 2020.) The Petra Nova CCS project in Texas pipelined its captured CO_2 to the Hilcorp West Ranch field. U.S. DOE (2020) reports that project stored approximately 3 Mt accompanied by it's own system of monitoring and accounting; Petra Nova's monitoring, verification and accounting program developed by the Texas Bureau of Economic Geology (U.S Department of Energy, 2020) was not submitted for approval to EPA under Subpart RR during the demonstration period.

The Core Energy EOR storage project is located in Northern Michigan along a trend of ancient carbonate reefs (Core Energy, 2018). CO_2 is captured from several shale gas natural gas separation facilities and transported to injection facilities through 80 miles of supercritical CO_2 pipeline network. Just over 2 Mt of CO_2 were injected by the project between 1996 and 2017 (Sminchak et al., 2020). The Midwest Regional Carbon Sequestration Partnership supports an ongoing MRV program operated by Battelle that has demonstrated secure storage at the site (Midwest Regional Carbon Sequestration Partnership (MRCSP, 2020) while testing commercial monitoring technologies such as vertical seismic profiling, satellite monitoring, neutron capture logging and borehole gravity surveys.

Occidental Petroleum's Wasson Field in the Denver Unit is located in the Permian Basin of West Texas, was discovered in 1936, and has an estimated original oil in place (OOIP) of 4 billion barrels, one of the largest in the U.S. Injections of CO_2 into the Permian San Andres Formation dolomites has been ongoing since 1980 (Occidental Petroleum, 2015). Approximately 213 Mt of supercritical CO_2 has been injected, and an estimated 129 Mt has been "stored" (note: Occidental uses the term "stored" for unrecovered injected CO_2 prior to the approval and implementation of its MRV plan) and 84 Mt produced. Occidental's model estimates that under its EPA-approved 2017 MRV plan, 200 Mt will be stored to 2120, which is about 25 % of the storage capacity of the Denver Unit. CO_2 has been and will be sourced from Occidental's Century natural gas plant and other pipeline sources.

Occidental Petroleum's Hobbs Field project in the Permian Basin of West Texas, has been injecting CO_2 since 2003 (Occidental Petroleum, 2017). Injected into the Permian San Andres Formation is approximately 31 Mt of supercritical CO_2, an estimated 14 Mt of which is "stored" (see note above). Occidental's model estimates that under its EPA-approved 2017 MRV plan, 119 Mt will be stored to 2120, which is about 27 % of the storage capacity of Hobbs field. CO_2 has been and will be sourced from Occidental's Century natural gas plant and other pipeline sources.

5.2. China's EOR-Storage Projects

Accompanying China's efforts to capture and utilize CO_2 are initiatives to monitor and quantify storage incidental to EOR. China's projects are typically small commerical projects, test or huff-*n*-puff injections involving tens of thousands of tonnes per year, unaccompanied by recapture /recycle of produced CO_2. The lack of recycle makes it difficult to estimate how much CO_2 is sequestered in rock pore space by capillary trapping, and presumably the produced CO_2 has been lost to the atmosphere. Indeed, Ma et al. (2018) correctly state "reporting only CO_2 sold/purchased is not secure storage" and identify important steps for accounting in such projects where recycle is not present (in addition to any leakage), such as accounting for vented CO_2 based on production data, and accounting for CO_2 entrained in oil sold to market. In the future, with recycle plants and advanced surveillance methods, CO_2 may be tracked and accounted for the purpose of storage and improved flood conformance may result.

Zhang et al. (2015) describe monitoring methods deployed in CNPC's Jilin EOR project, the largest CCUS demonstration project in China, in the time interval between 2008 and 2012. At the time, the program incorporated a number of subsurface methods, and surface measurements of atmospheric CO_2 flux and soil gas. Monitoring methods including mechanical integrity (cement bond logs, electromagnetic inspection/EMI) (CO_2 corrosion is a major concern in China relative to storage since injection wells have not been engineered for CO_2) microseismic, cross-well seismic, ESP, tracers and produced fluids. They concluded that 80 % of the CO_2 was stored in the H-59 block with 20 % lost to breakthrough in nearby production wells. Faults were determined to be largely non transmissive. Authors suggest above zone approach in the future as well as a recycle program for Jilin and estimate from reservoir simulation that only 66 % of CO_2 may be stored without recycle.

In Sinopec's Gaoqing 89 block EOR-storage monitoring project about 80 km from the city of Dongying in Shandong Province, monitoring and verification began in 2010 including time-lapse 3-D seismic data (Wang et al. (2018). The CO_2 at this site is a combination of captured CO_2 from the Shengli Power Plant, and captured industrial CO_2 and naturally occur. Ma et. al. (2018) reports that because there is no recycle system, all of the CO_2 is vented from the produced oil, in addition to some methane.(Of course, some of the CO_2 would have been retained in the rock by virtue of geological processes.) Scale-up of the Gao-89 EOR-storage project with CO_2 delivered by a supercritical-phase CO_2. pipeline from the Shengli plant, and a gas-phase pipeline from the nearby QiLu petrochemical (noted previously) has been limited by oil price fluctuations.

Li et al. (2018) have undertaken integrated monitoring in conjunction with CO_2-EOR in Yanchang Petroleum's Ordos Basin projects (Jingbian, Wuqi blocks) for the pre-operational, operations, post injection shutdown and site closure stages. Tools selected include wellbore integrity, surface deformation, fluid sampling, modeling.

6. Recommendations

CO_2 enhanced oil recovery with storage (CCUS) has the potential to play an important role in boosting China's domestic crude oil production, and at the same time mitigate fossil CO_2 emissions. Given the abundance of industrialCO_2, utilization can also offset the consumption of waterfor secondary flooding and therefore help reduce brine treatment and costs in China's arid oil fields. China's 2019 roadmap for CCUS sets out goals for moving CO_2 utilization from the R&D stage forward to the industrial stage. We believe China's efforts to expand beyond its pilot scale CO_2-EOR and storage projects could be further enhanced by infrastructure modernization, accompanied by technological and strategic innovations specific to China's challenging continental reservoir geology accompanied by supportive regulatory policies and incentives. The following observations and attendant recommendations gleaned from the successes of the U.S. projects may shine a light on some ways to improve results toward realizing large-scale commercial scale CO_2 flooding and attendant carbon storage.

6.1. Reservoir Selection

Is CO_2-EOR the first or last choice for ultra-low permeable and ultra-complex reservoirs in China? EOR should be reserved for best reservoirs. Poorly performing oilfields won't become good ones with CO_2. As illustrated in this paper, the low API crude depleted production reservoirs chosen for enhanced recovery are extremely low permeability, low porosity, highly fractured, under-pressured, which means achieving miscibility and high sweep efficiency is a difficult challenge. In the 2015 report by Yanchang Petroleum (Yanchang Petroleum, 2015), page 5, the following is cited as a reservoir selection criterion for their CO_2 flooding pilot projects in the Ordos Basin: "*Reservoir production poorly developed and in need of alternative development.*" Here CO_2 flooding is apparently being utilized as a tool to stimulate poorly performing reservoirs. Alternatively, by seeking the best candidates for CO_2 flooding rather than those that present a production challenge should lead to higher volumes of tertiary oil recovery.

6.2. Geologic Study

Most of China's petroleum reservoirs currently in operation are in thick continentally- derived clastic sequences, which are characterized by meandering channel and deltaic deposits rather than thick marine continental shelf sandstone deposits. Such deposits are characteristically compartmentalized and difficult to target and require advanced subsurface investigation methods in order to map and model sequence stratigraphic sections allowing for the identification of the thicker sands for targeted drilling.

6.3. Infrastructure Investment

CO_2 supply is critical; in tandem with choosing the best reservoirs for a CO_2 flood, access to reliable high-volume, low-cost captured CO_2 is important for successful and sustainable long-term commercial-scale EOR with CO_2 storage. Projects in the United States demonstrate that CO_2-EOR requires significant upfront capital investment that take several years to generate a positive cash flow, and a decade to achieve return on investment. Critical EOR facilities include recycle, separation and injection plants at all projects which impacts CO_2 availability and pipeline investment. Supercritical CO_2 pipelines enable high steady-state injection volumes and pressures and allow for optimization of hydrocarbon pore volumes (HCPV) & common carrier pipelines. Geologic carbon storage can only be accomplished in EOR settings with recycling facilities that ensure that treat CO_2 as a valuable commodity and keep the gas from reentering the atmosphere. Clearly China has recognized this, pipeline studies having been undertaken by the three major onshore companies. However, we understand that investment in CO_2 transport in China has lagged due to continuing low oil prices and weak CO_2 demand.

6.4. Beyond in-House Expertise

Chinese oil companies may prefer to undertake all aspects of exploration, drilling, well logging and stimulation and production in-house. However, even the most successful CO_2 flooding projects in the world rarely undertake all aspects of drilling and production. It is not unusual for projects in the U.S. to contract out drilling, well stimulation, development of corrosion-resistant tubulars, well logging, engineering design and construction –and where storage is involved, CO_2 monitoring design and implementation. Contracting service companies and consultants with global expertise may help projects leapfrog to success in such areas as modernizing injection and transportation infrastructure, flooding under-pressured reservoirs in tight highly fractured reservoir rock, conformance control and hardware corrosion.

6.5. Sharing Knowledge

Subsurface data and analysis are not typically shared and are rarely published in China's oil industry. Breakthroughs such as the U.S. shale revolution came, in part, from companies sharing strategies such as horizontal drilling and multi-stage fracs, effectively extending success upon the shoulders of previous successes. Greater sharing of geologic data, such as releasing well logs and publication of successful methodologies for the utilization of CO_2 could help expedite progress.

6.6. Monitoring, Verification and Accounting and Next-generation EOR Methods

A wide range of new subsurface tools and surveillance methods are utilized at today's CO_2 floods. Such methods include horizontal drilling, targeted infield drilling, and investment in new subsurface CO_2 flood monitoring technologies. Research suggests that these methods improve performance by contacting more reservoir rock. (DiPietro, 2014)."Next generation" EOR focuses on subsurface CO_2 management and surveillance strategies for improving CO_2 flood conformance—maximizing pore volumes of CO_2. This will have the effect of improving oil yields, but also result in enhanced storage by capillary trapping as the CO_2 flushes out oil with increased sweep efficiency. DiPietro cites several key approaches: 1) robust reservoir characterization, and 2) extensive monitoring, diagnostics and process control. Therefore, investment in and careful choice of subsurface tracking methods in the process of monitoring verification and accounting will also help an operator understand the subsurface and maximize sweep efficiency, and thus residual storage in these reservoirs. Many of leakage monitoring efforts in China have been based on surface CO_2 soil flux measurements, which can be confounded by seasonal variation and miss the opportunity to identify CO_2 migrating out of the subsurface geologic EOR/storage complex when it might be mitigated before it reaches the surface. All surface flux methods should be proven sensitive to leakage of CO_2 in the surface environment (e.g. perhaps so in arid regions such as in the Ordos Basin). Subsurface remote sensing tools include repeat seismic surveys, cross-well tomography and above zone monitoring interval (AZMI).

6.7. Identification of Residual Oil Zones

Over the past decade, operators in the Permian Basin and elsewhere have identified reservoir intervals that can be produced by CO_2 flooding below the conventional primary production reservoir, below the oil-water transition zone (Trentham et al., 2016). These are residual oil zones or "ROZ". Some ROZ plays are "greenfields" that do not have associated primary production. The petrogenesis of these intervals is related to late stage tectonic tilting that has resulted in natural artesian water flooding leaving, however, residual oil saturation that can be dislodged with CO_2. The identification of ROZs requires an understanding of tectonics combined with subsurface petrogenic analysis that extends below primary production. ROZs may extend the production of a field beneath the oil-water contact and improve output as well as increase stored volumes of CO_2.

6.8. EOR Alternative: Tight Sand Production Methods

The suitability of a reservoir for miscible CO_2 floods is strongly dependent upon the ability to bring the reservoir back approximately to its initial formation pressure. In order to do so, a reservoir must have sufficient injectivity, and lack fracture pathways that lead to rapid breakthrough rather than flood conformance. Hydraulic fracturing may increase access to formations that are impermeable, however they also decrease the ability to sweep oil and bring the formation up to miscible pressures. Part of the secret to success, as noted above, is choice of higher API crude reservoirs that are adequately permeable and porous. But where reservoirs do not exist, CO_2-EOR may not be the right choice, but instead the formation may need to be produced by methods that have been developed over the past decade to extract oil from tight formations such as in North Dakota's Bakken Formation. Such methods similarly rely on hydraulic fracturing in combination with horizontal drilling. Enhanced recovery methods have been researched for tight formations in the United States, however, capital requirements likely drive investment in new wells and prospects rather than enhancing existing reservoirs. Learning gleaned from the successes in developing America's tight sands may prove helpful in some of China's tight sandstone CO_2-EOR projects.

7. Conclusions

China has put much hard work into developing numerous CO_2 EOR projects to utilize and ultimately store its abundant industrial CO_2 in order to achieve its ambitious CO_2 reduction goals. While the tight continental geology and heavier oil pose significant challenges, there are several important directions China's operators could take to build upon its current infrastructure in order to achieve greater success. Investing in separation, compression and reinjection facilities at China's larger commercial projects will ensure adequate and consistent CO_2 supply for more effective floods, to reduce the cost of purchasing CO_2 and to ensure that maximal injected CO_2 is retained in the subsurface and stored... Capital investments are critical, along with an understanding that the return on investment will be longer than for conventional and unconventional oil production. Such investments would include building open access pipelines that will guarantee supercritical CO_2 supply, and ensure that adequate HCPV slugs are utilized, to maximize the sweep of CO_2 in these reservoirs and in turn, CO_2 stored. Sharing knowledge and building partnerships across Chinese companies as well as between China andWestern companies may spur innovation to address challenges faced by China in conducting CO_2-EOR and storage in its predominantly continental geology.

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CRediT authorship contribution statement

L. Bruce Hill: Conceptualization, Investigation, Data curation, Writing - original draft, Writing - review & editing. **XiaoChun Li:** Conceptualization, Investigation. **Ning Wei:** Conceptualization, Investigation, Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

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