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A feasibility study of the integration of enhanced oil recovery (CO_2 flooding) with CO_2 storage in the mature oil fields of the Ordos Basin, China

Yajun Wang[1, 2], Zunsheng Jiao[2, 3], Ronald Surdam[2, 1], Lifa Zhou[3], Ruimin Gao[4], Yongzhen Chen[2, 3] Tingting Luo[2, 3], Hong Wang[4]

[1]*State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an, Shaanxi, China*
[2]*Carbon Management Institute, School of Energy Resource, University of Wyoming*
[3]*Shaanxi Provincial Institute of Energy Resources and Chemical Engineering*
[4]*Research Institute of Shaanxi Yanchang Petroleum (Group) Co., LTD*

Abstract

Rich in energy resources, China's Ordos Basin shares many similarities with Wyoming's Powder River Basin. As a result, the experience and expertise pertaining to energy development in the Powder River Basin should prove helpful in the Ordos Basin. The basin's coal, coalbed methane and natural gas reserves are ranked first in China, and its oil reserves are ranked fourth. The coal deposits in the Ordos Basin account for 39 percent of total Chinese coal reserves (3.98 trillion tonnes), and six of the thirteen largest coal mines in China are located in the basin. The overlapping development of relatively new coal conversion industries with existing oil and gas industries in northern Shaanxi Province is creating an opportunity to apply the systematic approach developed in Wyoming: the integration of geological CO_2 storage and CO_2-EOR. The coal conversion industry (i.e., coal-to-methanol, coal-to-olefins, etc.) provides affordable, capture-ready CO_2 sources for developing large-scale integrated CO_2-EOR and carbon storage projects in the Ordos Basin, China. Compared with other CCUS projects, the ability to use CO_2 from the coal-conversion industry for CO_2-EOR and subsequent geological CO_2 storage will make integrated projects in the Ordos Basin more cost-effective and technologically efficient.

The low porosity, low permeability, low oil saturation, anomalously low reservoir pressure, and high reservoir heterogeneity of the target storage formations in the Ordos Basin make using CO_2 for enhanced oil recovery much more challenging here than in the US. These reservoir characteristics together constitute a major reason that CO_2-EOR is not widely employed in the Ordos Basin, even though sources of highly concentrated CO_2 (coal conversion plants) have been available for years. Comparisons of reservoir and crude oil properties in the Ordos Basin with the current US CO_2-EOR screening guidelines reveal that gravity, viscosity, crude oil composition, and formation type of the Ordos reservoirs all are favorable for CO_2 miscible flooding. The major challenges in deploying EOR result from anomalously low reservoir pressure, low porosity, and higher reservoir heterogeneity.

Keywords: CO_2-EOR, geological CO_2 storage, Ordos Basin

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Introduction

Enhanced oil recovery via CO_2 flooding (CO_2-EOR) is a widely accepted and effective tertiary recovery technique that has been used for decades in the United States of America: CO_2-EOR projects in Wyoming and Texas have demonstrated that CO_2-EOR techniques can routinely increase oil recovery by 5 to 20 percent, depending on reservoir conditions and applied technology. Concurrent with the stranded oil recovery, about one-third of the injected CO_2 remains in the subsurface during the CO_2-EOR process, while about two-thirds is recycled and recompressed for injection back into the reservoirs. At completion of production, the EOR project has significant potential to permanently store CO_2 in the depleted oil fields. The integration of geological CO_2 storage with enhanced oil recovery has proven effective in increasing oil and gas production, reducing CO_2 storage costs, and improving environmental protection.

Applying experience gained during CO_2-EOR and CCS projects in Wyoming, researchers at the University of Wyoming Carbon Management Institute are working closely with scientists from Northwest University, the Shaanxi Provincial Institute of Energy Resources and Chemical Engineering (SPIERCE), and the Yanchang Petroleum Company to expedite CO_2-EOR and geological CO_2 storage projects in the Ordos Basin. At present, many CCS projects focus on CO_2 emitted by coal-fired power plants. The higher energy consumption/penalty and costs of CO_2 capture from coal-fired power plants have become serious technical and financial obstacles for commercial-scale CCS and CO_2-EOR projects. In northern Shaanxi Province, the coal conversion industry (i.e., coal to methanol, coal to olefins, etc.) provides affordable, capture-ready CO_2. Compared with other CCS projects, the ability to use CO_2 from the coal conversion industry for CO_2-EOR and geological CO_2 storage makes these projects in the Ordos Basin cost-effective and technologically efficient.

The mature oil fields in the Ordos Basin are being screened and prioritized based on CO_2-EOR criteria and proximity to CO_2 sources (coal conversion plants). Three-dimensional reservoir characterization, CO_2-EOR potential, geological storage models, numerical performance assessments, and economic evaluations will be used to select sites in the basin for EOR/CO_2 storage demonstration projects.

Geological background

With an area of 370,000 km^2, the Ordos Basin is the second largest sedimentary basin in China and covers portions of the Shaanxi, Shanxi, and Gansu provinces, and the Ningxia and Inner Mongolia autonomous regions. Tectonically, the basin lies in the western part of the North China Block and is bordered by Luliang Mountain to the east, Qinling Mountain to the south, Liupan Mountain and Helan Mountain to the west, and Lang and Yin mountains to the north. Separated by the Great Wall, the basin is covered by the Maowusu and Kubuqi deserts in the north and the Loess Plateau in the south.

The Yellow River surrounds the basin to the west, north, and east: all hydrologic systems in the basin are part of the Yellow River drainage. Most tributaries in the desert and plain areas are intermittent streams that typically flow into desert lakes or salt marshes. Though its surface streams have small permanent flow and poor water quality, often drying out in summer, the Ordos Basin is rich in groundwater.

The Ordos Basin is a typical cratonic basin that developed into a large stable basin during the Paleozoic, with tectonic movements dominated by both regional uplift and subsidence. With the exception of uplifts and depressions that developed at the margins, the basin is characterized by a huge monoclinal structure (110,000 km^2) with a 1- to 2-degree dip to the west, called the Shaanbei Slope. The Shaanbei Slope is dominated by a relatively stable tectonic environment with rare regional faults, and therefore has good potential for geological CO_2 storage.

The basement is a metamorphic system of Archaen and Lower Proterozoic age. The basin has experienced five stages of evolution: 1) Mid to Late Proterozoic sedimentary sequence, 2) Early Paleozoic shallow foreland platform, 3) Late Paleozoic coastal plain, 4) Mesozoic inland basin, and 5) Cenozoic faulted depressions surrounding the basin margin. The Ordos Basin can be subdivided into six structural units as follows: the Yimeng Uplift, the Weibei Uplift, the Jinxi Fault-Fold Belt, the Shaanbei Slope, the Tianhuan Depression, and the Western Edge Fault Belt.

Oil, gas, and coal resources in the Ordos Basin

More than 40 oil fields have been discovered in the Ordos basin, including the Xifeng field – the largest oil field found in China in the past 10 years – with reserves of 400 million tonnes. Four of China's five gas fields with reserves of at least 100 billion cubic meters are located in the Ordos Basin, including Sulige, Jianbian, Wushenqi, and Yulin gas fields (**Figure 1**). The Ordos Basin contains more than 8 billion tonnes of equivalent petroleum resources, including about 11 trillion cubic meters of natural gas. In 2011, oil production from the Ordos Basin was 32 Mt. Annual oil production of the Ordos Basin is expected to exceed 35 Mt by 2020, and the annual production of natural gas is expected to reach 40 billion to 50 billion cubic meters in ten years.

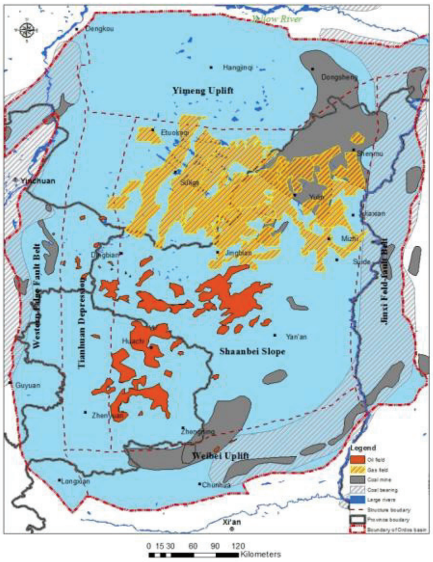

Figure 1. Maplshowing oil, gas, and coal fields in the Ordos Basin

Sources of anthropogenic CO_2 in the Ordos Basin

Along with being China's number-one energy producer, the Ordos Basin also hosts the nation's largest coal-to-chemical industry base. As more and more coal-to-chemical plants are built near the coal mines in the Ordos Basin, CO_2 emissions have increased correspondingly and dramatically.

Industrial sectors examined within the scope of this study include coal-fired power plants, coal conversion plants (methanol, acetic acid, diesel, ethylene oxide), cement plants, iron and steel plants, petroleum refining facilities, and ammonia plants. The CO_2 emissions calculation methodology used in this study is based on IPCC Guidelines for national greenhouse gas emissions and based on available plant capacities and productivity, as noted below:

$(ECO_2)_{ji}=(EF)_{ji} * (P_1)_{ji}$

$$(ECO2)ji = \sum_{i}^{n}\sum_{j}^{m}(ECO2)ji$$

Where $(ECO_2)_{ji}$ is the estimated annual CO_2 emissions of the i^{th} emission source within the j^{th} industry sector;
$(EF)_{ji}$ is the emission factor of the i^{th} CO_2 emission source within the j^{th} industry sector;
$(P_1)_{ji}$ is the production yield of the i^{th} CO_2 emission source within the j^{th} industry sector;
N is the number of industry sectors; and
M is the number of factories within sector i.

CO_2 emissions calculated for cement plants, refineries, iron and steel facilities, and ammonia plants are based on reported productions, while productive capacity was used for power plants.

We will present a preliminary map of stationary CO_2 sources in the Ordos Basin, including most stationary point-sources that emit at least 0.1 Mt of CO_2 per year, such as coal-to-chemical plants, coal-fired power plants, refineries, cement plants, and ammonia plants. As a result, this analysis does not consider all anthropogenic CO_2 emissions, and specifically does not include those from small industrial CO_2 point sources, transportation, the commercial and residential building sector, land use, agriculture, and others. The locations of industrial facilities were obtained from web searches, and latitude and longitude coordinates were assigned based on the center of the corresponding industrial site.

Results of this paper indicate that 43 large stationary CO_2 point sources in the Ordos Basin emit at least 0.1 Mt per year. Annually, CO_2 emissions from these sources total an estimated 290 Mt. Of this total, 40 Mt is capture-ready CO_2 (> 95% concentration) emitted from coal-to-methanol plants.

Lessons learned from current US CO_2-EOR projects

Over the past 40 years, CO_2 flooding has become a mature technology capable of effectively enhancing oil recovery in mature and mostly-depleted oil reservoirs in the US. CO_2 flooding has been shown to improve the efficiency of oil recovery significantly compared with primary (pressure depletion) and secondary (water flooding) recovery methods ([1] Koottungal, 2012; [2] Manrique et al., 2010).

Production from 120 individual US CO_2-EOR projects through 2012 averaged 352,221 barrels of oil per day (BOPD; [1] Koottungal, 2012), or approximately 6% of the total US crude oil production of 6 million BOPD. Of the CO_2-EOR production, 308,564 BOPD is from CO_2 miscible flooding, and 43,657 BOPD is from CO_2 immiscible flooding. CO_2 flooding technology has surpassed thermal technology (steam, in-situ combustion, and hot water) as the most commonly used method of tertiary enhanced oil recovery.

Miscible CO_2 flooding has achieved widespread use in the southwestern US, mainly in the Permian Basin of Texas, Rocky Mountain, and mid-continent regions of the country, along with some additional EOR production in Alaska partly related to CO_2 injection. The oil and gas industry generally handles CO_2 as a supercritical fluid, which is stable above the critical point of 6.9 MPa (1,087 psi) and 31°C (88°F). In its supercritical state, CO_2 injected into the reservoir behaves like a liquid with respect to density and like a gas with respect to viscosity. Under suitable reservoir pressure and oil compositions, injected CO_2 mixes with the crude oil within the reservoir, causing an increase in oil volume via oil swelling and a subsequent reduction of oil viscosity. This process eliminates interfacial tension between the oil and CO_2 and reduces the capillary forces that inhibit oil flow through the pores of the reservoir ([3] Brock and Bryan, 1989; [4] Shtepani, 2007; [2] Manrique et al., 2010). Theoretically, all contacted oil could be recovered under CO_2 miscible flooding ([4] Shtepani, 2007), although in the US, recovery is usually limited to about 5% to

22% of the original oil in place (OOIP). CO_2 flooding efficiency is affected by a number of parameters, including reservoir residual pressure, residual oil saturation, oil composition and viscosity, porosity and permeability, and sedimentary architecture – especially reservoir heterogeneity and natural fractures.

Based on years of laboratory and field tests, along with full-scale commercial operations, screening criteria for miscible CO_2-EOR have been suggested by several investigators ([5] Brashear and Kuuskraa, 1978; [6] Goodlett, 1986; [7] Taber, et al. 1997; [8] Klins, 1984; [9] Taber and Martin, 1983; [10] US DOE, 2010; [3] Brock and Bryan, 1989; [4] Manrique et al., 2010). CO_2 flooding has been successfully applied in both sandstone and carbonate reservoirs, and homogenous thin beds are preferred. In an optimal miscible CO_2 project, crude oil gravity should exceed 22 API; actual API in most projects ranges from 27 to 44. Recommended viscosity is less than 10 cp; viscosity in most projects ranges from 0.3 to 6 cp. Residual oil saturation should exceed 40%; oil saturation in current projects ranges from 15% to 70%. A high percentage of intermediate composition (C5 to C12) in the crude oil is favorable for miscible CO_2 flooding. Residual reservoir pressure is a critical parameter for CO_2 flooding projects, and many projects inject water to establish reservoir pressure before CO_2 flooding begins. Residual reservoir pressure must exceed minimum miscible pressure – in most cases represented by reservoir depth. Current project depths range from 2,500 feet to more than 11,250 feet (Beaver Creek Madison project, Wyoming; [11] Peterson et al., 2012). Reservoir temperature is not a critical screening criterion, but higher temperatures can increase the expandability of the crude oil. Porosity values vary widely in different depositional systems, but generally fall between 6% and 30% ([12] Beike and Holtz, 1996). The type of porosity, as well as the amount, is important: well-connected pores of similar size are best for CO_2-EOR miscibility projects. Permeability determines the fluid dynamics of the oil reservoir. High permeability allows large volumes of CO_2 to be injected via a single well, thus reducing costs. Homogenous high permeability allows CO_2 to move more quickly into the reservoir and increases sweeping efficiency.

Reservoir heterogeneity and natural fractures can potentially contribute to a CO_2 flooding project's lack of success, especially in depositional systems with highly variable vertical and horizontal permeability. Strata with very high permeability values can result in unstable flow (viscous fingering) resulting in early CO_2 breakthrough and reducing oil-sweep efficiency. To prevent unstable flow and reduce the amount of CO_2 needed for the process, CO_2 is typically injected into the reservoir alternately with water (WAG) because water sweeps through the reservoir more uniformly. The WAG can significantly reduce viscous fingering and allow CO_2 to flow through the reservoir after full miscibility is achieved.

CO_2-EOR potential and challenges in the Ordos Basin

Rich in energy resources, China's Ordos Basin shares many similarities with Wyoming's Powder River Basin. Therefore, the energy development strategy suggested for the Powder River Basin may prove applicable to the Ordos Basin. At present, most CCUS projects focus on capturing and storing CO_2 from coal-fired power plants. The greater energy consumption and higher cost of CO_2 capture from coal-fired power plants have become serious obstacles to commercial-scale CCUS and CO_2-EOR projects. The most prominent regional overlap of the coal-to-chemical and oil and gas industries occurs in Shaanxi Province (**Figure 1**), and availability of large quantities of nearly pure CO_2 associated with the coal-to-chemical industries has created an ideal environment to integrate CO_2-EOR with geological CO_2 storage in the Ordos Basin. Integrating these two critical elements increases oil and gas production and will significantly reduce anthropogenic CO_2 emissions in an important energy-producing region of China.

Most of the oil production in the Ordos Basin comes from the Triassic Yanchang Formation. The inter-bedded lenticular sandstone, siltstone, mudstone, and shale of the Yanchang Formation accumulated in fluvial, deltaic, and lacustrine depositional environments. The Triassic Yanchang reservoirs are characterized by low porosity, low permeability, low oil saturation, anomalously low reservoir pressure, and high heterogeneity. These characteristics directly resulted in very low primary and secondary recovery (less than 15%) in most of the basin's oil fields. **Table 1** shows reservoir and crude oil properties for selected Yanchang reservoirs.

Table 1. Comparison of Ordos reservoir/crude oil properties with the US CO_2-EOR screening guidelines.

Property	*US recommended*	*US current project range*	*Ordos*
Gravity	< 0.92 (> 22 API)	0.81–0.89 (27–44 API)	0.73–0.86 (33–62 API)
Viscosity	< 10 cp	0.3–6 cp	1.3–9 cp
Composition	high percentage of C5 to C12	light to intermediate	light to intermediate
Oil saturation	> 40%	15%–70%	40%–56%
Formation	thin beds	sandstone/carbonate	thin sandstone beds
Porosity	> 8%	4%–18%	5%–17%
Permeability	not critical	3–31 md	0.1–7 md
Depth	> 800 m (2,600 ft)		200–2,500 m (650 –8,200 ft)

Depths of selected reservoirs range from 150 to 2,200 meters. The thicknesses of individual sandstone beds range from 7 to 15 meters. Porosity values range from 8% to 17%, and permeability ranges from 0.5 to 38 md, but in many cases is less than 1 md. The formation water type is calcium chloride with a high total dissolved solids content, ranging from 10,000 to 70,000 ppm. The reservoirs are regionally underpressured, and were underpressured even at the beginning of field development. The quality of crude oil is light or intermediate, with specific gravity ranging from 0.72 to 0.84, or 35 to 62 API. Most reservoirs have oil saturations ranging from 40% to 60%. Because all reservoir sandstones were deposited in fluvial and lacustrine environments, very low continuity and high heterogeneity is common for most reservoirs. Natural fractures with significantly different orientations are found in most cores from the Yanchang reservoirs.

The low porosity, low permeability, low oil saturation, anomalously low reservoir pressure, and high reservoir heterogeneity make using CO_2 to enhance oil recovery in the Ordos Basin more challenging than in the US. These characteristics together constitute one of major reasons why CO_2-EOR projects are not widely developed in the Ordos Basin, though sources of highly concentrated CO_2 (from coal conversion plants) have been available for years. All Yanchang reservoirs are anomalously underpressured, with a pressure coefficient of 0.9 (0.39 psi/ft). Therefore, the residual pressures for most candidate reservoirs are below the minimum miscible pressures.

Table 1 compares the reservoir and crude oil properties with the current US CO_2-EOR screening guidelines (assembled from the literature, especially [7] Taber et al., 1997; [4] Shtepani, 2007; and [13] Lake et al., 2008). Based on gravity, viscosity, crude oil composition, and formation type, the Yanchang Formation reservoirs are favorable for CO_2 miscible flooding. The major challenges result from anomalously low reservoir pressure, low porosity and permeability, and higher reservoir heterogeneity.

Though a CO_2-EOR project in the Ordos Basin will face some challenges, many conditions favorable for developing CO_2-EOR projects in the Ordos Basin exist. In addition to available substantial local CO_2 sources, the thin beds and fluid-flow compartmentalization favor the establishment of stable flow and could increase sweep efficiency. Reservoir pressure is one of the most important factors for determining CO_2 miscibility in oil. According to [14] Klins and Bardon (1991) and [4] Shtepani (2007), it is possible to achieve a different level of miscibilities, ranging from immiscible (low-pressure reservoirs) through intermediate- to high-pressure applications (miscible displacement). The minimum miscibility pressure has a wide range of values depending on depth, temperature, and crude oil composition. However, a minimum of 8 MPa (800 meters, 1,180 psi) is generally regarded as a target reservoir pressure at which to conduct a successful CO_2 flood. This condition imposes an important restriction related to the current level of reservoir pressure for miscible CO_2 flooding of Yanchang reservoirs. A significant number of reservoirs in the Ordos Basin fall below this level (**Figure 2**).

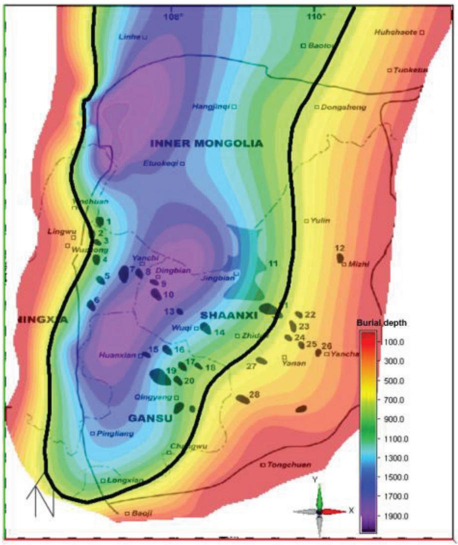

Figure 2. Oil fields in the Yanchang Formation plotted on a map of burial depth of the Yanchang Formation.

Figure 2 shows oil fields superimposed on a map of burial depth of the Yanchang Formation. The thick black line represents the 800-meter contour of the burial depth of the Yanchang Formation. Oil fields located in the area encompassed by the black line in the diagram (**Figure 2**) have present-day depths of at least 800 meters. Because the oil and gas reservoirs in the Ordos Basin typically have a very low percentage of movable formation water, water flooding may not be effective for enhanced oil recovery. Injecting CO_2 into the reservoirs before any production occurs could be an efficient way to establish the reservoir pressure necessary to meet the minimum miscible pressure requirement. A numerical simulation of pre-CO_2 injection for building the reservoir pressure has been generated for a variety of different CO_2 injection scenarios. In one simulation, the average depth of the targeted reservoir was 1,500 m, and the reservoir had a porosity of 10%, and permeability of 1 md. The injection rate of supercritical CO_2 was 23 kg/minute. The residual reservoir pressure is anomalously underpressured at 11.5 Mpa. The simulation results from Los Alamos National Laboratory's FEHM simulator show that minimum miscible pressure could be established for this reservoir after 100 days of supercritical CO_2 injection.

Generally, CO_2 flooding of Yanchang oil reservoirs will be challenging, but with careful inventories, detailed reservoir characterization, systematic prioritization of EOR targets, and a surplus of CO_2, early EOR successes in the Ordos Basin will be possible.

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