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Cluster deployment of sequencing for carbon capture, usage as water filters and storage at Yulin, Shaanxi Province, China

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ABSTRACT

After the national "30.60" carbon peaking and carbon neutrality goals were proposed, Yulin City in Shaanxi Province, an important energy base in China, came under intense pressure to reduce emissions because of its rich fossil energy reserves and large number of coal chemical and coal-fired power plant enterprises. As a result, it urgently needs to switch from high emission to low carbon. In this paper a four-dimensional seismic forward modeling is established to prove that the geological conditions of the area are suitable for CO_2 geological storage and CO_2 can be monitored in this area. Then the CO_2 emissions of major industrial parks and counties in Shaanxi Province were summarized the Yulin City's current CO_2 capture, utilization, and storage (CCUS) industrial chain was organized. Last but not least, the following recommendations were made for the development of the CCUS cluster in Yulin: (1) Yulin is appropriate for large-scale CO_2 capturing activities due to its highly concentrated emissions and matured CO_2 capturing technology. (2) Since the cost of transporting CO_2 to its storage location by tank truck is significant, it is suggested that a pipeline be constructed to transport the gas in order to reduce costs. (3) Despite the promise of CO_2-EOR (CO_2-enhanced oil recovery) in Yulin, geological storage in a deep saline aquifer close by is now the preferred method due to the emission source's distance from the oilfield. (4) Two CO_2 geological storage demonstration projects in Yulin City are still centered on oil displacement at the moment. It is necessary to conduct surveillance research on the volume of CO_2 storage and use the CCUS method to define the accounting boundary. Yulin's geological sequestration of CO_2 is now too small to satisfy the urgent requirement for significant emission reductions. It is vital to draw lessons from industrialized nations' experience, establish scientific research institutions for CO_2 geological sequestration, and then design innovative and motivating policies in technology, supply chains, and commercial models that can extend the CCUS scale.

Keywords: CO_2 emission; CO_2 capture; CO_2 sequestration; CO_2 capture, utilization, and storage cluster; Cluster deployment

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1. Introduction

CO_2 capture, utilization, and storage (CCUS) technology is the only viable option for China to reach its carbon peak and carbon neutrality objectives [1–4]. Although there is a lot of CCUS cluster project planning worldwide, there is minimal study on CCUS project clusters in China. For instance, the Nercem Cement Factory in Brevik and the Fortum Waste Incineration Plant in Oslo will both use carbon capture as part of Norway's Longship CCUS Cluster Project. The CO_2 that was captured will be carried to the CO_2 treatment facility, and after that, it will be transported to the North Sea to be injected into the saline aquifers for geological storage [5]. A CCUS center has also been planned for the Gulf Coast of the United States since it has numerous emission sources and acceptable geological characteristics [6]. Due to the similar environmental circumstances between the Ordos Basin and the American Gulf Coast, it should be appropriate to deploy CCUS hubs in the Ordos Basin.

The second-largest sedimentary basin in China, the Ordos Basin is situated in the country's central and western regions (Fig. 1) and is home to numerous abundant energy sources as well as a sizable domestic and regional energy and chemical base [7]. Moreover, it has a solid geological structure with minimal faults, cracks, and earthquake events as well as numerous linkages between reservoirs and caps with significant storage potential [7]. The Ordos Basin's geological storage capacity for CO_2 has been anticipated by a number of academics. Ren et al. [7] examined and calculated the oil and gas reservoirs, coal seams, and salt and saline aquifers in the Ordos Basin, for instance, and made a preliminary prediction that the geological storage capacity for CO_2 would be in the range of tens of billions of tons. Through the analysis on the storage potential of Ordos Basin, Yang et al. [8] concluded that the CO_2 storage potential of the deep saline water layer and oil reservoir was 13.3 billion tons, and the storage capacity of 56 suitable CO_2 storage areas involved in Yanchang Petroleum reached 1.77 billion tons [8].

Yulin, the most complete region of the CCUS industrial chain in Shaanxi Province, is situated in the northeastern portion of the northern Shaanxi slope of the Ordos Basin (Fig. 1). This region is rich in fossil energy resources. Moreover, as the core territory of the "Golden Triangle" of energy and chemical industry, it has developed its energy and chemical industry and established an industrial chain system of coal-to-olefin, coal-to-aromatics, coal-to-oil, and coal salinization integration promoted by coal pyrolysis, establishing a modern coal chemical industry system of coal carbonization-gasification-hydrogenation-methanol-olefin-power generation integration, and poly-generation comprehensive utilization [9–11]. Due to the significant emissions produced by the coal chemical industry, coal-fired power stations, and other energy-consuming businesses in Yulin, the national "carbon peaking and carbon neutrality" aim and dual control of energy consumption are posing serious obstacles.

Yulin City produced 27.29 million tons of oil and gas equivalent in 2021, accounting for 5.5% of the nation's output in crude oil, 10.31% in natural gas, and 13.5% in coal (550 million tons) production. As a result, it is regarded as the most favorable place in China for the development of CO_2 capture, utilization, and storage (CCUS) technology due to its high source and sink matching, stable geological structure, and enormous storage capacity [12–15]. With the help of CCUS technology, CO_2 may be extracted from coal-fired power stations, chemical factories, and other sources of high emissions, compressed, liquefied, and transported to a storage location by tank truck, pipeline, or ship. In this process, CO_2 can be injected into oil fields at a later stage of development, which not only improves oil recovery but can also be sealed or directly injected into a stratum of salty water for storage. In this paper, a four-dimensional seismic forward modeling of the CO_2 geological storage area is established using geological and logging data. It is believed that the CO_2 stored in the area can be monitored by four-dimensional (4D) seismic, ensuring the safety of CO_2 geological storage. Based on this, the status quo of CO_2 emission and CO_2 capture and storage in Yulin is combined with the introduction of two extant demonstration projects of CO_2 geological storage in Yulin, and the advantages and disadvantages of the two demonstration projects are compared and analyzed. Ultimately, the Yulin CCUS cluster construction plan was proposed.

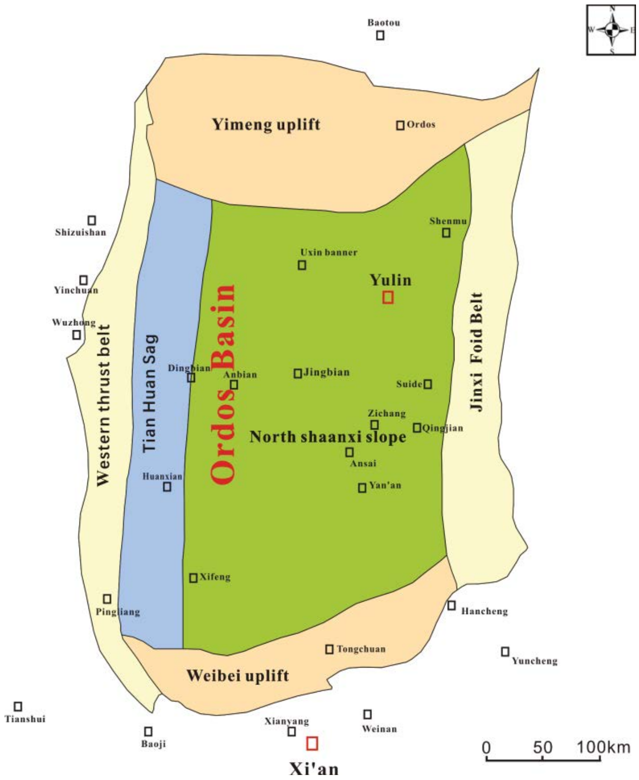

Fig. 1. Ordos Basin.

2. Establishing 4D seismic forward modeling

For the feasibility of 4D seismic, a two-layer medium model is established based on the oil-bearing reservoir and caprock of well Huang 234 in Huang 3 block of Ordos Basin. The caprock data above Huang 234 oil layer is processed by square wave, and it is assumed that the caprock elastic parameters remain unchanged during CO_2 injection

(Table 1). On this basis, the P-wave and S-wave velocities and densities under different pore pressure and CO_2 saturation are calculated, and it is assumed that the elastic parameters of caprock remain unchanged during CO_2 injection. The parameters are shown in Table 1. On this basis, different strata are calculated P-wave, S-wave velocity and density under pressure and CO_2 saturation.

Firstly, under the original pore pressure, the CO_2 saturation in the reservoir is calculated as 0%, 10% and 20%, respectively, Reflection coefficient at 30% (Fig. 2). It can be seen from the figure that the reflection coefficient decreases with the increase of incident angle. The black solid line is the reflection coefficient when CO_2 is not injected, and the other lines are the reflection coefficients at different saturation after fluid replacement. It can be seen that the reflection coefficient decreases gradually with the increase of CO_2 saturation, and the greater the saturation, the less obvious the change. That is, the reflection coefficient changes after CO_2 injection. It is sensitive when CO_2 saturation is small, but the difference of reflection coefficient is not obvious with the increase of CO_2 saturation. This is very similar to AVO characteristics of tight gas bearing reservoirs.

Secondly, the reservoir fluid saturation remains unchanged, and the pressure changes, that is, the reflection coefficient is calculated every 2 MPa (Fig. 3). Comparing the AVO curves of saturation change and pore pressure change, it can be seen that the reflection coefficient is more sensitive to pore pressure change.

The AVO gradient and intercept are calculated by Zoeppritz equation, and the intersection drawing of gradient and intercept is established. The P-wave velocity, S-wave velocity and density of the above four different saturation and pore pressure are calculated, respectively, and the gradient and intercept are negative. It is consistent with the characteristics of class III gas bearing sandstone (Shi and Zhao, 2002). This also shows that the seismic response of supercritical CO_2 injected into underground reservoir is similar to that of natural gas, and class III gas bearing sandstone is the gas bearing reservoir most easily detected by conventional seismic technology in Ordos Basin.

Figs. 4 and 5 are the gradient intercept diagrams of CO_2 saturation and pressure, respectively, and the star is the AVO gradient and intercept of the original reservoir. It can be seen that the AVO gradient and intercept change obviously with the change of pressure. This shows that the difference of seismic amplitude between CO_2 injection and pre-injection increases significantly with the increase of injection pressure. The difference of seismic amplitude after injection can be well monitored by 4D seismic technology. The differential variation of amplitude does not depend much on CO_2 saturation, which is mainly the reflection of pore pressure variation.

Finally, the synthetic seismic seismogram of the well model is made by using the data of well Huang 234 (Fig. 6). Fig. 6b shows that the fluid saturation remains unchanged,

Table 1
Caprock parameters of two-layer medium model in well Huang 234

	Caprock
P-wave velocity (km/s)	4.242613
S-wave velocity (km/s)	2.447378
Density (g/cm^3)	2.424532
Porosity (%)	5.310907
Shale content (%)	18.9253389

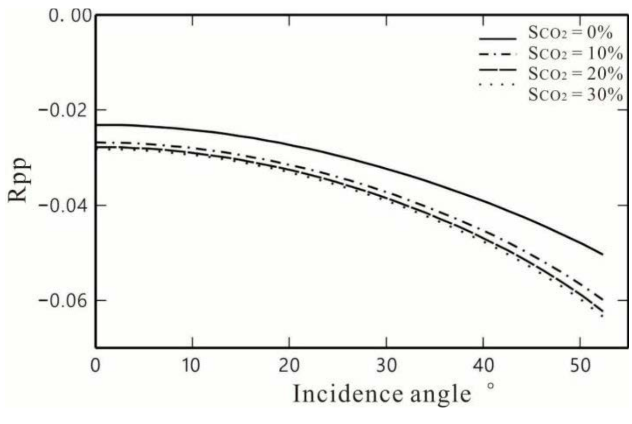

Fig. 2. AVO curve with CO_2 saturation when pore pressure is 29.77 MPa.

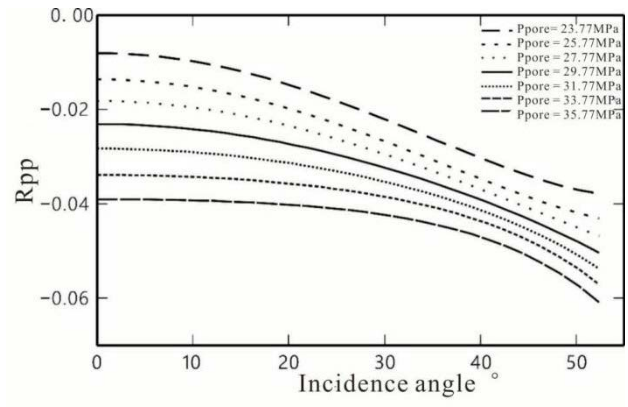

Fig. 3. AVO curve with constant fluid saturation and pressure change.

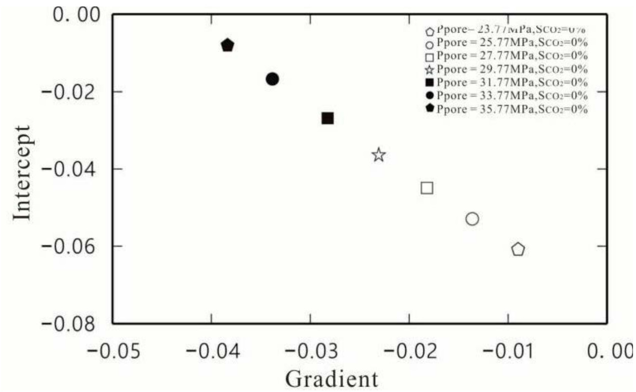

Fig. 4. Gradient-intercept varying with pressure when CO_2 saturation is 0.

and only the pore pressure changes by 5 MPa. Fig. 6c shows that the pore pressure remains unchanged, while the CO_2 saturation is 20%. The difference synthetic seismogram in Fig. 6b is more obvious. This shows the importance of considering the changes of pressure and fluid saturation in the establishment of 4D seismic forward model, and also shows the feasibility of deploying 4D seismic in this area when the pressure change is 5 MPa or even greater.

3. Discussion

By establishing a 4D seismic forward modeling, it can be known that the feasibility of deploying 4D seismic in this area when the pressure change is 5 MPa or even greater. It indicates that the safety of CO_2 geological storage through 4D seismic monitoring in this area is feasible, and predicting the amount of CO_2 geological storage is feasible. Furthermore, we have organized the demonstration projects for CO_2 capture and CO_2 geological storage in the Yulin region. Provide theoretical and data to support for deploying CCUS hub.

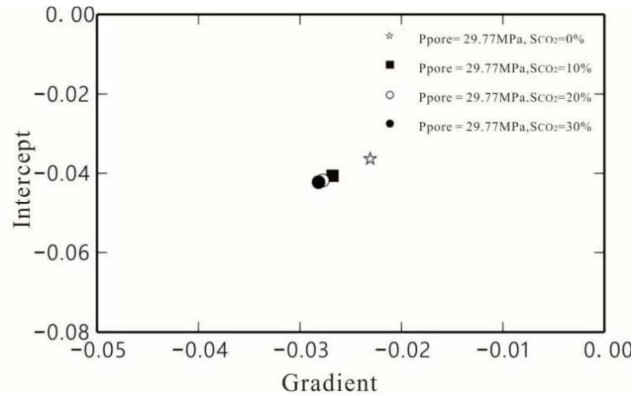

Fig. 5. Gradient-intercept variation with CO_2 saturation when pore pressure is 29.77 MPa.

3.1. CO_2 capture project in main industrial parks of Yulin City

Yulin is not only abundant in fossil fuels like coal, natural gas, and oil but has also flourished in the electric power and coal chemical sectors, making it both a significant source of carbon emissions and an important energy town in China. The primary source of carbon emissions in Yulin is the industrial utilization of fossil fuels, with the electric power sector accounting for the biggest share (43.98%) of this total. Compared to the coal chemical industry, the coal-fired power stations' flue gas has a low percentage of CO_2 (between 11% and 15%), making it more challenging to capture. The coal chemical business is the emission source with the lowest cost of capturing CO_2, making it the most suitable for CCUS. The concentration of CO_2 in the flue gas released by this industry can reach up to 75%–99%. Fig. 7 displays the carbon source statistics of the coal chemical facilities near Yulin. Fig. 8 depicts the CO_2 capture initiatives in Yulin that are currently under construction or have been completed.

The numbers in the figure represent the names of enterprises: 1 - Shaanxi Yulin Kaiyue Coal Chemical Co., Ltd.,

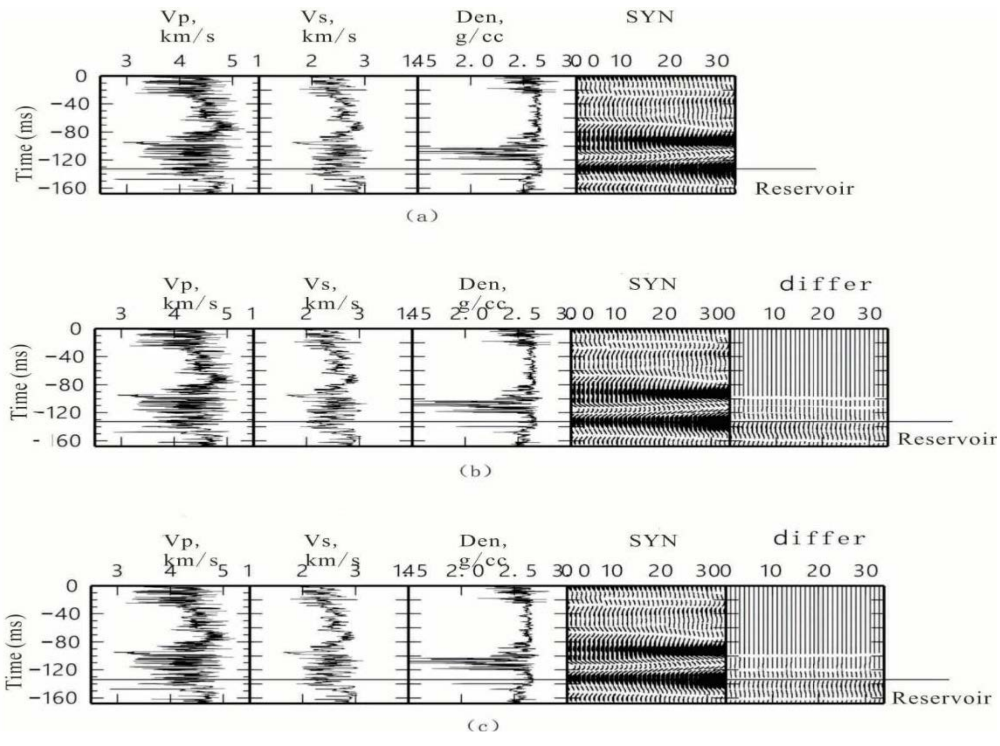

Fig. 6. Synthetic seismic seismogram of original pore pressure of (a) 29.77 MPa and CO_2 saturation of 0%, (b) 34.77 MPa and CO_2 saturation of 0%, and (c) 29.77 MPa and CO_2 saturation of 20%.

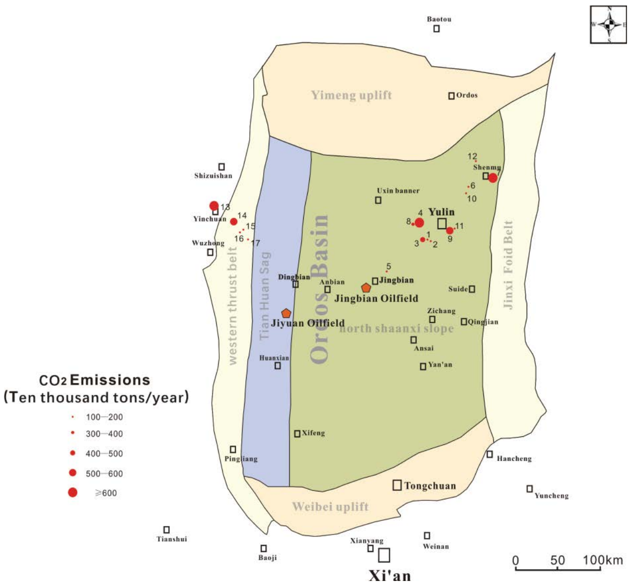

Fig. 7. Statistical table of carbon sources in Yulin and its surroundings.

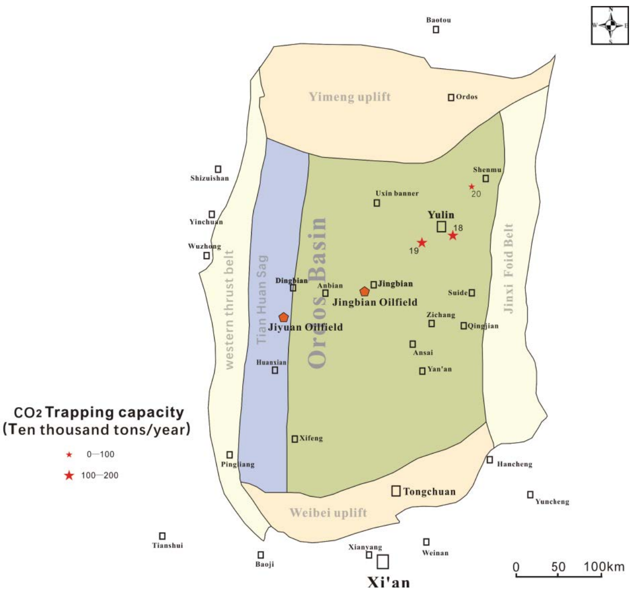

Fig. 8. CO_2 capturing project in Yulin City. Numbers represent the name of the enterprises 18 - Yulin Chengtou Baisheng Chemical Technology Co., Ltd., (Yulin, China), 19 - Shaanxi Yanchang Zhongmei Yulin Energy and Chemical Co., Ltd., (Shaanxi, China), 20 - Shaanxi Guohua Jinjie Energy Corp., (China).

(Shaanxi, China), 2 - Shaanxi Yanchang Petroleum Yulin Coal Chemical Co., Ltd., (Shaanxi, China), 3 - China Coal Shaanxi Yulin Energy & Chemical Co., Ltd., (China), 4 - Shaanxi Weilai Energy & Chemical Co., Ltd., (Shaanxi, China), 5 - Shaanxi Yanchang Zhongmei Yulin Energy and Chemical Co., Ltd., (Shaanxi, China), 6 - Shaanxi Shenmu Chemical Industrial Co., Ltd., (Shaanxi, China), 7 - Shenhua Group (China), 8 - Yankuang Group (China), 9 - SHCCIG Yulin Chemical Co., Ltd., (China), 10 - Shaanxi Yanchang Petroleum Yushen Energy Chemical Co., Ltd., (China), 11 - Shaanxi Yulin Energy Group Co., Ltd., (Shaanxi, China), 12 - Shenmu Longhua (China), 13 - Ningxia Coal Group (China), 14 - Ningxia Baofeng Energy Group Co., Ltd., (China), 15 - Sinopec Great Wall Energy and Chemical Co., Ltd., (China), 16 - Ningxia Hening Chemical Co., Ltd., (China), 17 - Ningxia Kunpeng Clean Energy Co., Ltd., (China).

The two pentagons, which represent the locations of the demonstration projects for CO_2 geological storage, Jiyuan oilfield and Jingbian oilfield, respectively.

In order to address the issue of high concentration CO_2 emission reduction in the coal chemical project of China Coal Shaanxi Yulin Energy and Chemical Co., Ltd., (China) and create space for carbon emissions, Yulin Chengtou Baisheng Chemical Technology Co., Ltd., (Yulin, China) (Fig. 8) has planned and built a project of comprehensive utilization of coal chemical tail gas with an annual output of one million tons of CO_2, 20,000 tons of ammonium bicarbonate, and 10,000 tons of industrial ammonia.

In addition to offering premium chemical goods, Shaanxi Yanchang Zhongmei Yulin Energy and Chemical Co., Ltd., (Shaanxi, China) (Fig. 8) is dedicated to the comprehensive utilization of kerosene and gas resources. In 2016, it also carried out a feasibility assessment for a 360,000-ton CO_2 capture equipment. In September 2021, the company and PetroChina Engineering Corporation planned a 5-million-ton CO_2 capture project with an expenditure of RMB 785 million to build a 1.6-million-ton CO_2 booster purification station. The low-temperature methanol product tower, which released CO_2 in two quantities with a 98% and 70% concentration, is where the captured CO_2 was produced. The construction of the 1.6 million-ton-per-year capturing operation was divided into two phases. During the initial stage of construction, 340,000 tons of CO_2 with a 98% concentration and 420,000 tons with a 70% concentration were captured. A pressurized purification unit with a capacity of 700,000 tons will be constructed in the second phase, and its ability to capture CO_2 will be increased to 1.6 million tons, or 890,000 tons of high-concentration CO_2 and 710,000 tons of low-concentration CO_2.

The Jinjie Power Plant, owned by Shaanxi Guohua Jinjie Energy Corp., (China) (Fig. 8), has an installed capacity of 3.72 million·kW and an annual CO_2 emission of over 10 million·tons. It helps China achieve its "carbon peaking and carbon neutrality goal" by enabling low-carbon development in high-carbon industries. The company constructed the largest post-combustion CO_2 capture facility in China, with a capacity of 150,000 ton/y, and successfully completed a 168-h trial operation at a time. The coal-fired power plant has a CO_2 emission concentration of 11% to 15% and utilizes a composite amine chemical absorption mode, wherein the flue gas is conveyed to a water washing tower via a pipeline for water washing, then enters an absorption tower for CO_2 low-temperature absorption, enters a regeneration tower for high-temperature desorption of CO_2 gas, and is ultimately compressed, dried, and cooled to produce liquid CO_2. The project now generates industrial-grade qualified liquid CO_2 with a purity of 99.5% and is the largest post-combustion CO_2 capture facility for coal-fired power plants in China. Shaanxi Guohua Jinjie Energy Corp., (China) is performing the front-end research and commercialization demonstration model study for a large-scale CO_2 collection, use, and storage project of more than 1 million·ton/y as a result of the positive experience of this demonstration project.

3.2. Overview of CO_2 geological storage demonstration project in Yulin

Two CO_2 displacement and geological storage projects have been completed in Yulin: the first is the CCS Demonstration Project in Jingbian County of Yanchang Petroleum, starting gas injection in September 2012, and the other one is the CO_2 displacement and storage demonstration project in Dingbian County Huang 3 of Jiyuan oilfield, a subsidiary of PetroChina Changqing Oilfield, starting gas injection in July 2017.

3.2.1. General situation and analysis of the CCS Demonstration Project in Jingbian County of Yanchang Petroleum

The CCS Demonstration Project in Jingbian County (Fig. 7) is a CO_2-EOR (CO_2-enhanced oil recovery) project, with a cumulative CO_2 injection volume of 93,000 tons. Its primary development horizon is the Triassic Chang 62 reservoir. With five CO_2 injection wells that correspond to 33 beneficiary wells and an enhanced oil recovery of 8.5%, gas injection began in September 2012 by alternating CO_2 and water injection [21]. For this demonstration project, the workflow of CCUS is as follows:

(1) CO_2 is transported by a tank truck to the storage site, unloaded and stored in the cryogenic tank.
(2) CO_2 in the low-temperature tank is transported to the compression pump by pipeline for compression.
(3) The compressed CO_2 is transported to the wellhead by pipeline, where it is injected into the ground alternately with water.
(4) After CO_2 and water are injected underground, what is produced in the production well is a mixture of oil, water and CO_2, where CO_2 is not recycled.

The first geological storage and CO_2 displacement project in Shaanxi Province is the Jingbian CCS project. On the basis of this, it is suggested that a 5-million-ton geological storage project for CO_2 be designed and then injected into the Chang 6 reservoir. Due to the large number of wellheads in Jingbian area (about 1,000 injection wells), the pipeline is designed for supercritical pipeline transportation. According to the current workflow, the design of previous projects tended to oil displacement and enhanced oil recovery, and little attention was paid to CO_2 geological storage [22,23]. Nonetheless, the following recommendations were made for this project in light of the current carbon peak and carbon neutrality goals:

(1) The emission of a significant volume of CO_2 suddenly will cause individuals to suffocate, hence attention should be paid to CO_2 leaks. Even if it does not threaten human safety, CO_2 leakage will cause the emission of greenhouse gases, defeating the purpose of CCUS in the long run. In this project, there may be leakage from the tank truck to the storage tank, from the storage tank to the compression pump, and from the compression tank to the wellhead. However, neither the storage tank nor the transportation pipeline has a device to monitor any CO_2 leaks. Particularly, there are numerous wellheads in this region, making wellhead monitoring essential.
(2) As an emission reduction technology, CCUS needs to account for the energy consumption of the whole well site during the carbon accounting, including but not limited to the compression pump and the exhaust system in the plant where the compression pump is placed, which is not considered in this demonstration project.
(3) After CO_2 displacement, CO_2, water and oil are collected. As newly captured CO_2 is not recycled, that is, part of CO_2 is directly discharged into atmosphere after being collected through wellhead after injection. It is recommended to install CO_2 recovery device in production well to recycle CO_2, which not only saves cost for purchasing CO_2, but also ensures that CO_2 storage is a closed-loop process.
(4) It would appear inappropriate for the demonstration project to substitute CO_2 injection volume for CO_2 storage volume. Geophysics (4D seismic) is now the only practical method for monitoring and verifying the caprock and overburden during the injection operation, particularly once the storage phase is complete [24–27]. The geological storage can be observed in greater detail using 4D seismic monitoring technology on the ground, which provides a three-dimensional view of the reservoir and caprock integrity and fluid distribution [27–29].

3.2.2. General situation and analysis of the CO_2 displacement demonstration project in Dingbian County Huang 3 of Jiyuan oilfield

Changqing Oilfield Oil Production Plant No. 5 (Changqing, China) belongs to Changqing Oilfield Company (Changqing, China), mainly responsible for developing Jiyuan oilfield (Fig. 7). The pilot test area of Huang 3 is constructed in two phases. The first phase was completed and put into operation in July 2017, with an injection horizon of Chang 8_1 member, a depth of 2,750 m, and a CO_2 miscible pressure of 16.1 MPa. The cumulative injected CO_2 volume reaches 147,000 tons, achieving a good effect with 15.1% higher than the injection development recovery rate. The process of the demonstration project is as follows:

(1) CO_2 is transported to the test station by a tank truck and then stored in a low-temperature storage tank with compression pump and cooling equipment to keep the phase state of CO_2.
(2) The liquid CO_2 from the low-temperature storage tank is input to the wellhead through the pipeline and directly injected into the underground by continuous CO_2 injection.
(3) After the injection, the oil, CO_2 and water produced by production wells will pass through the separation unit for recycling. The separated water will be directly treated on site and injected underground.

Final goal of the demonstration project is to build a zero-carbon well site, which has the following characteristics:

(1) All pipelines and storage tanks on the site were equipped with CO_2 leakage monitoring devices to handle CO_2 leakage, if any.
(2) The installation of CO_2 recovery unit in the production well ensured that the CO_2 geological storage is conducted in a closed loop.
(3) Neither surrounding environment monitoring on the surface of the leakage nor underground monitoring after CO_2 injection were made for leakage. The concept of CO_2 injection is applied instead of sequestration.
(4) The well site is equipped with sewage treatment facilities. Oil, CO_2 and water extracted from the ground would be separated and treated by the sewage treatment facilities before re-injecting into the ground. As an emission reduction project, greenhouse gas emitted during the treatment process should also be considered.

Since the Dingbian County Huang 3 is closer to Ningdong Chemical Industry Park (China) than the CO_2 capturing sources in Yuheng and Yushen Industrial Parks in Yulin City, its CO_2 mainly comes from the tail gas CO_2 capturing facility of coal chemical industry in Ningxia Deda Gas Technology Development Co., Ltd., (Ningxia, China). Given the locations and jurisdictions of these facilities, identification of inter-provincial emission reduction can be tricky. In other words, if the CO_2 captured in Ningxia transported to Shaanxi for storage, which province should the emission reduction be contributed to and would grant the incentive subsidies [30–33]?

4. Some obstacles restricting the development of CCUS in Yulin

The key to achieving the energy transformation and carbon peaking and neutrality targets under the presumption of providing energy security in China is the large-scale emission reduction through CCUS in Yulin, the national energy golden triangle [34,35].

The economics, transportation expenses, and a lack of incentive policies are the barriers that prevent the spread of CCUS, despite the fact that the oil recovery ratio has been greatly increased in the two present CO_2-EOR projects [36,37]. Construction of pipeline transportation to replace the current tank truck transportation is the key to cutting costs from the standpoint of oil displacement in oil companies, commencing with CO_2-EOR [38,39]. Nevertheless, building a CO_2 pipeline requires a substantial initial investment, and it is yet unclear who will finance the project and how long it would take to break even [40].

The net emission reduction of the project needs to be confirmed by CCUS methods, aside from the cost of the CO_2-EOR project. The current CO_2-EOR project cannot provide many of the metrics needed by the CCUS approach because it is still not standardized and has not yet been implemented. Also, there are regions where the CCUS methodology has to be enhanced so that projects can only get government incentives after their net emission reductions have been verified.

The close-by storage of CO_2 in deep salt aquifers can help high-emission businesses cut their emissions by lowering the cost of transportation of CO_2 [41]. Yet choosing the right location is also important for saline aquifer storage. In Yulin City's industrial parks, which are highly populated and business-intensive, the security of CO_2 saline aquifer storage will become a crucial element. In order to develop an efficient CO_2 geological storage technology suitable for the low porosity and low permeability saline water layer in the Yulin area, several experiments and researches are undoubtedly required for CO_2 injection and monitoring in saline aquifer. They include testing the business model and supervision model of CCUS operation, as well as the scientific innovation, technological innovation, policy innovation, and business model innovation of CCUS. Among them, the construction of CCUS technology infrastructure, particularly the construction of scientific research facilities for CO_2 geological storage [41], is the key to driving Yulin CCUS to form a large-scale cluster. It is also how industrialized nations like Japan and Australia are advancing CCUS demonstration and technology.

5. Understanding and conclusions

The entire CCUS cluster creation procedure should be implemented in accordance with the plan shown in Fig. 9. Also, the following recommendations are made to encourage the development of the Yulin CCUS cluster:

(1) The 4D seismic forward modeling indicates that the pressure change is greater than 5 MPa, and the injected CO_2 can be monitored by the 4D seismic. The characteristics of low porosity and low permeability reservoirs in the Ordos Basin determine that the CO_2 injection process requires high-pressure injection, where changes in formation pressure can monitor the injected CO_2. It is feasible to conduct CO_2 geological storage.

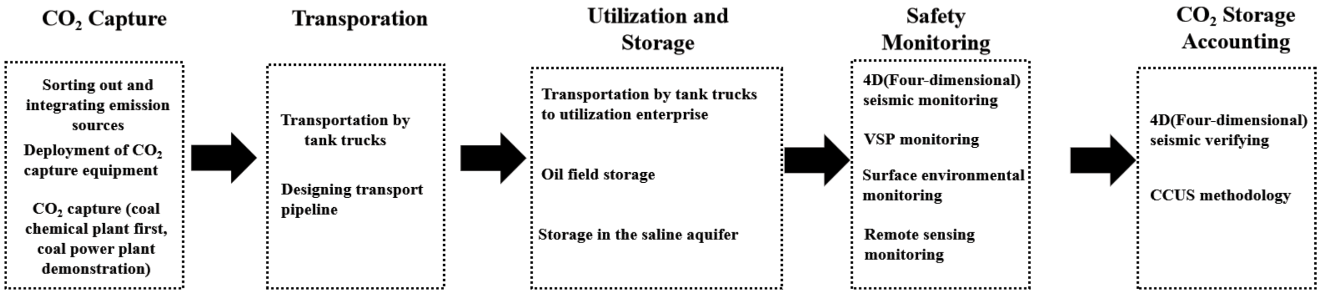

Fig. 9. CO_2 capture, utilization, and storage cluster deployment process.

(2) Building a CO_2 geological storage powered CCUS cluster: Yulin has a significant concentration of CO_2 emission sources and high annual emissions due to its position as the national energy and chemical industry's hub. After CO_2 is captured, the most important factor is to solve the problem of the location. Initially, the closest oil reservoir and saline aquifer that are ideal for CO_2 geological storage should be chosen in order to reduce emissions from the two high-emission industrial parks, Yuheng and Yushen. In order to accurately estimate the CO_2 geological storage potential in Yulin and provide fundamental information for the construction of a CCUS cluster, the scope of storage location should be further expanded [41] and the accurate location suitable for CO_2 geological storage in Yulin City should be optimized.

(3) The most cost-effective method for storing CO_2 in the earth is the CCUS cluster. To assess the expense of capturing businesses in terms of emission reduction, the location, CO_2 emission concentration, and emissions of each industrial park should be sorted out. The optimized pipeline laying scheme should be proposed around the storage area to avoid large underground coal mining areas and collapse areas. A large-scale network of pipelines should be used to transfer the CO_2 gathering and transportation station to the CO_2 geological storage area [42,43]. Only their own task must be finished by the businesses in each section of the chain. The coordination work should be completed by means of CCUS clusters, which can significantly reduce the expenses of companies and boost their enthusiasm.

(4) In order to realize the commercialization and sustainable operation of the CCUS cluster, Yulin must first learn from the experience of developed nations how to construct significant fundamental scientific research facilities for CO_2 geological storage and continue to conduct scientific research, technological innovation, and business model innovation. Meanwhile, the scientific research facilities are also the bases for training talents [44] who will serve the construction and operation of the future CCUS cluster in Yulin City.

5.1. Challenges

China's CCUS technology is in its infancy, and few research has been conducted on CCUS clusters. At its early stages of development, the CCUS center requires substantial financial assistance as well as pertinent national policy support [45,46]. The 45Q Tax Credit of the United States, the carbon levies of Norway and Canada [45,47,48], and some other developed nations' more intricate incentive programs are only a few examples of developed nations' experiences that worth learning. Instead of focusing on the injection quantity, we should utilize the emission reductions that CCUS has accomplished as the benchmark for incentives. We should also treat these reductions as being equivalent to those made by forest carbon sinks and include them into the carbon market. We suggest that priority be given to the incentive measures for pilot CCUS in Yulin City, where the CCUS projects in Shaanxi Province are most concentrated. For instance, the emission reductions from CCUS projects should be counted in the carbon market, and CCUS projects should be encouraged using the same strategies as solar and wind energy incentives.

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Author contributions

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