CCS: A China Perspective

Yanchang Petroleum Report 1:

Capturing CO_2 from Coal to Chemical Process

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1 Background and introduction

1.1 Climate change

Climate change caused by greenhouse gas emissions is one of the most serious challenges in the world today. As the world's second largest economy, China has made remarkable achievements in economic development over the past three decades. At the same time, China's carbon emissions have increased and reaching 9.8 billion tonnes in 2014.[1] The Chinese Government attaches great importance to climate change, enacted the "China's National Plan on Climate Change for 2014–20"[2], and planned to "Integrate the mitigation and adaption to climate change demands into all aspects of economic and social development, and to accelerate the construction of green low-carbon development model with Chinese characteristics."

1.2 The importance of coal in China's energy structure

China has abundant coal reserves. Coal constitutes 70% of China's primary energy consumption and coal fired power stations provides 80% of total electricity.[3] Clean coal technology development and deployment have become the major focus of coal utilization in recently years in China. Abundant coal resources are located in Northern China in regions such as Xinjiang, Inner Mongolia, Shaanxi and Ningxia, where the coal to chemical industry has boomed in recent years. The coal to chemical process generally emits large amount of CO_2. For example, the total CO_2 emissions may reach 42 million tonnes per year from the eight coal to chemical projects (in construction or in operation) approved by the central government of China (local government projects excluded).[4] This report focuses on reducing carbon emission from coal to chemical processes, and will not discuss carbon emissions from coal-fired power stations.

1.2.1 Coal chemical industry in China

After the development of more than half a century, China now has the largest coal to chemical industry in the world. The coal to chemical industry in China includes not only the traditional coal to chemical industry, of which the main products are synthetic ammonia, methanol, hydrogen, coke, calcium carbide, and other derivative products (such as fertiliser, soda ash,

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[1] BP 2015. *Statistical Review of World Energy June 2015*.
[2] China National Development and Reform Commission 2014, *China's National Plan on Climate Change for 2014-2020*, Beijing.
[3] Zhu. C 2012. "Discussion of Coal Power Related to China's Energy Security". *Sino-Global Energy.* Vol.17, no.1.
[4] Zeng. R 2013. "China may play a demonstrating role in CO_2 sequestration". *China Science Daily.* 18 September. p. 4.

formaldehyde, and acetic acid), but also the new coal to chemical processes developed in the last ten years, such as synthetic natural gas (SNG), coal to liquids (CTL), coal to methanol/olefins/propylene, coal to ethylene glycol and coal to methanol-aromatics (MTA). These new coal to chemical processes have been commercialised at substantial scales except coal to MTA, which is still in industrial demonstration stage. Some of the major coal to chemical projects in China are shown in Table 1.

TABLE 1 Representative coal to chemical projects in China

Coal to Chemical Project category	Description
Coal-based Fertiliser	In 2012, synthetic ammonia capacity had reached 67.30 million tonnes per year, and coal-based production accounted for more than 80%. The fertiliser industry consumes as much as 73.42 million tonnes coal per year.
Coking coal	In 2008, coking coal production capacity was about 328 million tonnes per year in China, accounting for 60% of world production. The steel industry consumes 87% of all the coking coal, and the chemical industry consumes 7.3%.
Coal to methanol	In 2012, methanol production capacity in China was around 51.49 million tonnes a year, and the actual amount produced was about 26.40 million tonnes per year, the coal consumption was about 31 million tonnes a year.
Coal to SNG	The four coal to SNG projects approved by NDRC have a total production capacity will reach 15.1 billion cubic meters per year. The total production capacity of all projects (including the ones under construction and the ones proposed) may reach a production capacity of 162 billion cubic meters a year.
Coal to oil	China has successfully demonstrated direct and indirect coal to oil technologies. Four demonstration projects have been successfully commissioned and in stable operation. The total capacity (including the planned projects) may reach 20 million tonnes per year.
Coal to MTO/MTP	Eight projects with a total production capability of 3.86 million tonnes a year have been commissioned. The total capacity of all projects may reach 12.29 million tonnes per year.
Coal to ethylene glycol	There are more than 20 coal to ethylene glycol projects under construction or planned, and their total capacity may reach more than 5 million tonnes per year.

1.2.2 Key aspects for coal to chemical process

Coal gasification is an essential step for coal to chemical processes (except for coking coal and calcium carbide production). The major CO_2 emission source is in the process of syngas production through gasification. To better understand the origin of such emission, it is necessary to look at the different aspects for a coal to chemical process.

(1) Gasification technology

China has adopted almost all of the large scale coal gasification technologies. For historical reasons, a large number of small fertiliser enterprises still use atmospheric fixed bed coal gasification technology. Since 1990s, almost all new coal to chemical projects used advanced high efficiency pressurized gasification technology. Among those technologies, entrained-flow gasification technology is dominating. The gasification technology may be coal/water slurry-based or dry coal powder-based. Further, for coal to SNG process, fixed bed dry bottom (FBDB) pressurized gasification technology is widely applied.

(2) CO_2 removal from raw syngas

Syngas produced from coal gasification usually needs to go through shift reaction and acid gas removal in order to meet the criteria for downstream production processes. Currently, the most widely used technology for syngas CO_2 removal is low temperature methanol wash process. Hot potash CO_2 removal process, polyethylene glycol dimethyl ether (NHD) carbon removal and amine-based (MEA, DEA, MDEA) are also used by industry. There are a few fertiliser and coke oven gas utilisation projects that adopted pressure swing adsorption (PSA) carbon capture technology. Although various carbon removal technologies have their own technical features, they have one thing in common that they emit high concentration CO_2. The CO_2 concentration generally exceeds 60mol%, and some emissions contain even up to 98mol% CO_2. In the case of low temperature methanol wash process, high concentration CO_2 are emitted from different units of the process and the stream of 98mol% CO_2 accounts for 30-50% of the total emissions.

(3) Characteristics of CO_2 emissions from coal to chemical process

The flue gas emitted from traditional fossil fuel combustion processes only contains around 3%-15% CO_2 at low partial pressures, and as a result the carbon capture costs are relatively high. However, the high concentration CO_2 emitted from coal to chemical process is easier to further concentrate (if required) and to compress. Advanced coal to chemical process usually starts with coal gasification which may then be followed by shift reaction and acid gas removal. Depending on the final products, different routes may then be used after carbon removal process, as shown in Figure 1. CO_2 is generally separated from shift reaction outlet gas. The acid removal technology emits large amount of CO_2 which has a concentration of more than 95%. Such high concentration CO_2 is ideal for geological storage. Nonetheless, there are other

CO_2 emission points in a coal chemical process, and these emission points contain a very low CO_2 concentration. Although these parts of gas are also of concern, they are not being considered in this report.

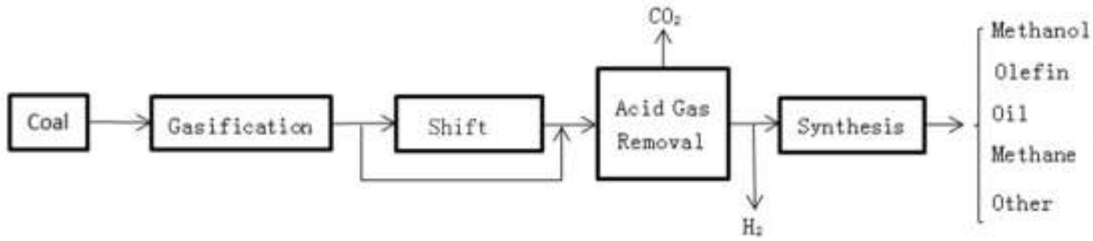

FIGURE 1 Typical coal conversion flow chart

It is widely agreed that large amounts of concentration CO_2 is emitted in such process. Generally, the ranking of CO_2 emission quantities for different coal conversion processes is (from high to low): coal to chemical or olefin; indirect coal to liquid; coal to methanol; direct coal to liquid. The high concentration CO_2 emission has become the bottleneck that restricts the development of coal to chemical industry.

1.3 Carbon capture utilization and storage (CCUS) in coal chemical industry

CCUS helps to achieve large scale reduction of greenhouse gas emission and to enable sustainable use of fossil fuels. As a climate change strategy, many countries have invested in the development and deployment of CCUS technology. CCUS is strongly supported by the Chinese Government's National Development and Reform Commission (NDRC), Ministry of Science and Technology (MOST), Ministry of Environmental Protection (MEP), and has also been included in the "China's National Plan on Climate Change for (2014-20)."[5]

As a means of large scale emission reduction, CCUS technology can be used in coal-fired power stations, gas power stations, natural gas processing, coal to chemicals, fertilizers, iron and steel, cement and other industries. Industrial carbon capture is already a relatively mature technology, particularly in natural gas processing and synthesis gas carbon removal, where CO_2 partial pressure is high and carbon capture costs are relatively low.

As mentioned above, the coal to chemical industry has boomed in Northern China regions, such as Xinjiang, Inner Mongolia, Shaanxi, Ningxia and Shanxi, where large amount of CO_2 is emitted. Meanwhile, there are many large sedimentary basins in the north western China, such as Songliao Basin, Bohai Bay Basin, Erlian Basin, Erdos Basin and Junggar Basin. Those basins have high sedimentary thickness, large reserves of oil, gas and coal resources, stable sedimentary structures, and good CO_2 reservoir, which provides good foundations for the

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[5] China National Development and Reform Commission 2012. *China's National Plan on Climate Change for 2014-2020.* Beijing.

deployment of whole chain CCUS. Therefore, the utilization of high concentration of CO_2 emitted by coal to chemical industry for EOR and permanent storage in the reservoirs within an oil-gas basin in close proximity to coal chemical plants can not only overcome the relatively high costs of purchasing high concentration of CO_2 from elsewhere, but also save transportation costs.

1.4 Overview of Yanchang Petroleum CCUS program

CCUS work at Yanchang Petroleum are supported by China NDRC and MOST. Yanchang Petroleum launched China-Australia CCUS Integrated International Cooperation Demonstration Project in 2013. The Project has also been accredited as a "National Science and Technology Support Project" and "863 Project".[6] Yanchang Petroleum has invested RMB300 million and set up a CCUS technology working group. Furthermore, Yanchang Petroleum also joined US-China Clean Energy Research Centre Advanced Coal Technology Consortium and established CCUS cooperation mechanism with University of Wyoming, West Virginia University and University of Regina.

Yanchang Petroleum built the first CO_2 capture plant (50,000 tonnes per year) in November 2012 at its Yulin Coal Chemical Company. In 2014, Yanchang Petroleum started the work for the second CO_2 capture plant (360,000 tonnes per year) at Yulin Energy Chemical Company. Along with the construction of the two CO_2 capture plants, Yanchang Petroleum started CO_2 storage and flooding pilot test. The Jingbian Qiaojiawa pilot test started in September 2012 and as of July 2014, the cumulative injected CO_2 reached 17,000 tonnes. The number of test injection well group was five in July 2014 and there are plans for expansion in 2015. After expansion, the injected CO_2 may reach 200,000 tonnes per year, whereas stored CO_2 will reach 120,000 tonnes per year. Furthermore, Yanchang Petroleum started the second CO_2 storage and flooding test area in 2014 in Wuqi Shaanxi to carry out miscible-phase flooding experiments.

Based on the experiences learned through demonstrations and pilots, new coal to chemical projects are included in CCUS planning by Yanchang Petroleum. A conservative estimate indicates that by the end of 13^{th} Five-Year Plan period (2016-2020), the high concentration CO_2 produced by Yanchang Petroleum will reach 4 million tonnes per year, and hence Yanchang has started the preliminary feasibility work for a 4 million tonnes per year CCUS project.

[6] "National Science and Technology Support Project" is a funding established in 2006 by MOST to encourage research and development of major science and technology issues in social and economic development; "863 Project" is a funding established in 1986 to support the development of novel advanced technology development, demonstration and deployment.

2 Clean coal strategy and CCUS project overview

2.1 Coal to chemical projects

The coal to chemical projects of Yanchang Petroleum are located in Jingbian Industry Development Zone, Yuheng Coal Chemical Industry Zone, Yushen Industry Zone and Yan'An Fuxian Industry Zone. The coal to chemical projects (in operation or under construction) include:

- Yanchang Petroleum and China Coal joint project: Coal-oil-gas to olefin project;
- Yulin Coal Chemical Company: Acetic acid project;
- Xinghua Fertilizer Plant Expansion project;
- Yulin Oil Refinery: Oil-coal co-refining project;
- Yan'An Energy Chemical Company : Coal-oil-gas integrated utilisation project;
- Shaanxi Future Energy (Yanchang Petroleum as shareholder): Coal to oil.

The planned coal to chemical projects will take full advantage of resources and technology of Yanchang Petroleum. These projects are aimed at converting coal resources to environmental friendly value-added clean oil products, ethylene propylene alcohol and high carbon alcohol.

2.2 Overview of Yanchang Petroleum CCUS project

Ordos Basin in north western China is the most important energy-chemical base with abundant oil, gas and coal resources. By taking full advantage of those resources, coal-fired power generation, coal to chemical and petroleum chemical industry have developed rapidly. As a consequence, Ordos Basin will become one of the largest CO_2 emission areas in China. Therefore, the implementation of CCUS in this area would make significant contribution to China's emission reductions.

Located in Ordos Basin, Yanchang Petroleum has initiated and implemented a new approach to energy conservation and emission reduction by co-utilising oil, gas and coal comprehensively in methanol production to reduce CO_2 emission in the first place. At the same time, the implementation of integrated CCUS work will increase oil recovery and achieve geological storage of CO_2. So far, Yanchang Petroleum has constructed two capture projects including Yulin Coal Chemical Company's 50,000 tonnes per year project and Yulin Energy Chemical Company's 360,000 tonnes per year project as shown in Figure 2.

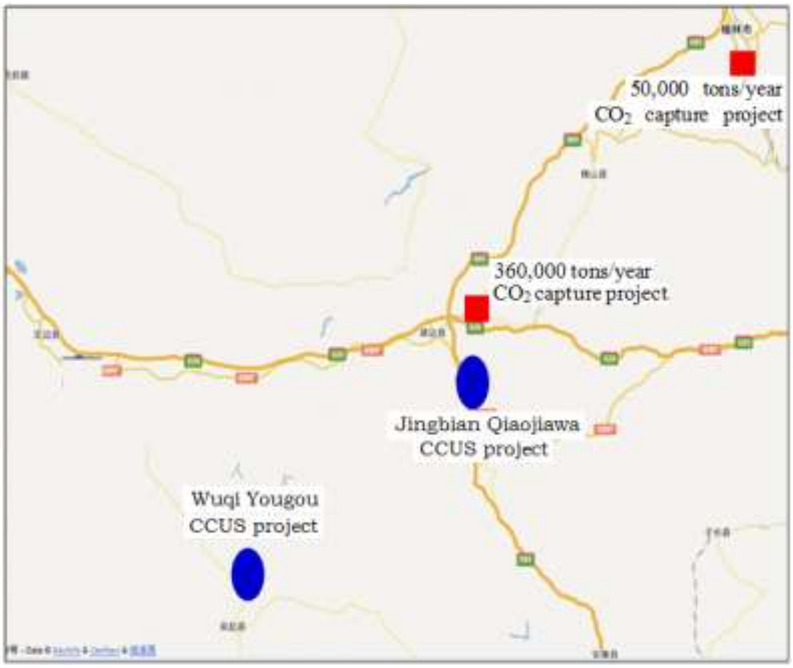

FIGURE 2 Location of CO2 capture and storage

3. Selection criteria for carbon capture technology

Carbon capture and storage is considered as an important emission reduction technology by the international community. Carbon capture accounts for majority of the cost of a whole chain CCS process, and high capture cost is the bottleneck for the deployment of CCS. In order to select the most suitable technology, Yanchang Petroleum conducted research about the capture technologies used by domestic and international CCS projects and carbon capture technologies supplied by some engineering companies. Considering its actual situation and the specific conditions of its coal to chemical process, Yanchang Petroleum has established a techno-economic selection criteria for carbon capture technology:

- The process should has great simplicity in terms of process operation and control;
- The process should have a small foot print considering the space constraints in a coal to chemical complex;
- The utilities consumption such as power consumption, nitrogen, instrument air, and water should be comparatively low;
- If solvent technology is used, fresh solvent supplement should be comparatively low;
- The process shall have high hydrogen recovery rate;

- The auxiliary refrigeration station for cooling should be relatively simple;
- The process should have comparatively low waste emissions (zero emissions if possible). The processes should discharge no methanol oil, thus avoiding the treatment unit of ammonia and cyanide methanol waste;
- Technology vendors are required to have significant experiences in synthesis gas CO_2 removal in coal chemical industry and have successful precedents;
- The technology should have relatively reasonable technology license fee.

A systematic comparative analysis of technology-business proposal tendered by domestic and foreign vendors was performed by expert panel established by Yanchang Petroleum. After conducting a comprehensive cost benefit analysis using the selection criteria, Yanchang Petroleum selected the best solution that is acceptable to all panel experts and management. From these key technical and economic selection criteria, it can be found that the predominant requirement of Yanchang Petroleum capture technology is that the technology should have a comparative advantage in energy and material consumption, operations and environmental waste emissions. Yanchang Petroleum hopes that these standards and criteria can be used as a reference for other similar projects.

4 Yulin Energy Chemical carbon capture project

4.1 Project description

Shaanxi Yanchang China Coal Yulin Energy Chemical Co. Ltd. (Yulin Energy Chemical) is a joint venture company between Yanchang Petroleum and China National Coal Group Corporation (ChinaCoal) with a registered capital of RMB7.0 billion. It was founded in May 2010. The company produces polyethylene and polypropylene at its large coal chemical, gas chemical and petrochemical integrated Jingbian facility. The facility includes five processing units and produces 1.8 million tonnes of methanol, 0.6 million tons of MTO, 0.6 million tonnes of polyethylene (PE), and 0.6 million tonnes of polypropylene (PP). In November 2009, Jingbian chemical industry project was named “Clean coal technology demonstration and promotion project” by NDRC and the United Nations.[7]

The project was established in June 2008 and put into production in 2014. The estimated investment is RMB25.973 billion and expected annual sales revenue is RMB17.286 billion. The company uses multiple-stage planning for the development of this facility. Towards the end of the first stage construction, a second stage will be launched, which will be focusing on the

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[7] China Net 2013. *Yanchang Petroleum “Oil-Gas-Coal-Salt co-utilization”.* Retrieved 19 June 2015. <http://news.china.com.cn/txt/2013-03/29/content_28393963.htm>.

diversifying olefin production chain and building multiple subsequent processing units. The planned third stage will take into account the availability of local resources and environment capacity. Upon completion of the development, the company plans to transform the industrial park into an integrated energy chemical facility with an annual revenue of over RMB100 billion.

At this facility, a CO_2 capture plant with the capacity of 0.36 million tonnes per year was designed and built for this project. Currently, the compression and liquefaction station proposal had been approved by Yanchang Petroleum and moved into design stage.

4.2 General principle of the capture process

This facility uses coal and associated gas as raw material for methanol synthesis. The combination of coal and gas yields better hydrogen to carbon ratio, so that the shift reaction load is reduced. Maximum utilisation of carbon may be achieved in the production of syngas. Shift reaction outlet gas goes through a low temperature methanol wash process for CO_2 removal. Liquid methanol at low temperatures has strong absorption for acid gas (H_2S, CO_2) and other feed gas impurities, and the solubilities for H_2S, CO_2 and other impurities are different. Therefore, low temperature methanol wash can be used to remove the acidic gases and other impurities (COS, HN_3, HCN) to produce qualified syngas for downstream methanol synthesis. At the same time, the process captures and concentrates CO_2, and CO_2 stream has an average concentration close to or over 80mol%. At this facility, the capture process takes into account the EOR flooding and storage requirements and produces a stream containing 98mol% CO_2. The refrigeration energy for the process is provided by a separate cryogenic cycle, using propylene as the working fluid.

4.3 Description of the capture process

The technology used in this project is based on the principle of physical absorption, wherein carbon dioxide, hydrogen sulphide and mercaptan may be absorbed by methanol. The cleaned synthetic gas containing hydrogen, carbon monoxide flows out from the top of the tower for downstream methanol synthesis. This capture process uses a five-column unit, including pre-wash, raw gas cooling, combined two-stage absorption, carbon dioxide regeneration, nitrogen stripping, hydrogen sulphide concentration, methanol liquid regeneration, methanol liquid dehydration as shown in Appendix Figure A-1.

Raw syngas from the gasification process unit (40-50°C) needs to be cleaned by methanol spray jet and be dehydrated in order to prevent ice forming that can block the pipeline and other equipment. Before entering the absorber, there is a heat exchanging process between syngas, carbon dioxide, exhaust gas, and purified syngas to reduce the temperature of raw syngas and at the same time, increase the temperature of each product gas for the downstream use.

The first primary absorber is divided into two parts, including the bottom part for sulphur compounds absorption and top part for carbon dioxide absorption. Clean syngas on the top of the absorber will be sent to the downstream process unit. Lean methanol solvent is pumped into the absorber by lean solvent pump. In the absorber, raw syngas and methanol solvent flow counter currently, and carbon dioxide and sulphur compounds are absorbed. At the same time, a circulation loop is equipped for the carbon dioxide absorption stage and it was designed to reduce the temperature increase caused by the absorption of carbon dioxide, thereby improving the absorption of carbon dioxide. Temperature of the absorber is about -50°C with a pressure of 56bar.a. Clean syngas contains no more than 0.2% of carbon dioxide, and less than 0.1ppmv hydrogen sulphide.

Rich solvent from sulphur compounds and carbon dioxide absorption sections in the first tower flows into the second tower after a series of flash process. In the second tower (carbon dioxide product tower), the pressure is approximately 2.5bar.a. and temperature is approximately -40°C. Carbon dioxide-rich solvent is taken to the upper portion of the second tower, and carbon dioxide is desorbed because of pressure reduction (through expansion) and desorbed carbon dioxide is then sent to carbon dioxide product line after heat exchange to recover cold energy. Sulphur-rich solvent is sent to the central section of the second tower, while methanol solution containing sulphur compounds and carbon dioxide at the bottom of the second tower is sent to the third tower (nitrogen stripping tower).

In the nitrogen stripping tower (concentration tower), multiple streams from the second tower enter the third tower from the top and middle sections. Nitrogen gas entering from the bottom of the tower reduces the partial pressure of carbon dioxide and thus promotes the further desorption of carbon dioxide. Nitrogen and carbon dioxide mixture gas flows out of the top of the third tower and goes through the raw gas cooler (raw syngas heat exchanger) recovering cold energy before being emitted.

After heat exchanging, flashing and pressure increasing by booster pump, hydrogen sulphide-rich solvent flows into the fourth tower (hydrogen sulphide desorption tower). In the hydrogen sulphide desorption tower (also called the methanol regeneration tower), the hydrogen sulphide-rich fluid flows into the tower from the top, heat is provided for the regeneration solutions by a steam reboiler at the bottom of the tower. Hydrogen sulphide and carbon dioxide are desorbed and the mixture gas flows out from top of the fourth tower, after cooling reflux, hydrogen sulphide-rich gas is sent to the sulphur recovery unit and the condensate is pumped back to the fourth tower.

Regenerated methanol is pumped into the 5th tower (methanol-water separation tower). In the methanol-water separation tower, methanol and water are separated by distillation, based on the boiling point difference. Regenerated methanol liquid from the 4th tower enters from the upper portion of the tower. There is a low pressure steam reboiler at the bottom. Evaporated gas (mainly methanol) is returned to the 4th tower, and the liquid at the bottom is mainly water, containing traces of methanol.

4.4 Major equipment

Major equipment of the process include methanol scrubber, CO_2 product tower, H_2S concentration tower, thermal regeneration tower, methanol-water separation tower, recycle gas compressor, rich/lean pump, spiral tube heat exchanger and propylene refrigeration units.

4.5 Capacity and efficiency of capture device

The process material balance is presented in Table 2. The removal rate of CO_2 from raw syngas is 99.25%, from an acid gas removal perspective. From a carbon capture perspective, the capture rate is the ratio of CO_2 in production gas and CO_2 in feed gas, and the calculated capture efficiency is 44.716%.The CO_2 product gas and the directly emitted CO_2 are both key emission sources for carbon capture. However, there are more than 30mol% N_2 in the directly emitted gas, and it costs more to capture CO_2 from such gas. Therefore, from an economic perspective, it is more cost effective to use the high concentration CO_2 product gas. According to mass flow rate of CO_2 product gas, CO_2 capture capacity of Yulin Energy Chemical Project is 45,049kg/h, and the annual CO_2 capture capacity is 360,400 tons, assuming 8,000 hours operation per year.

TABLE 2 Material balance of CO2 capture plant at Yulin Energy Chemical

Name	Feeding gas	Synthesis gas	CO_2 product gas	CO_2 emitting gas	Sulphur recovery of acidic gas
Nm^3/h	242255	189589	23232	37993	3792
mol%					
H_2	37.62	48.06	0.04	0.03	0.07
N_2	0.37	0.47	0.33	31.34	0.50
CO	40.04	50.99	0.76	0.41	0.22
Ar	0.13	0.16	0.00	0.00	0.00
CH_4	0.10	0.12	0.013	$<$0.01	0.00
CO_2	20.91	0.20	97.50	66.62	60.74
H_2S+COS	0.60	0	0.00	0.00	38.38
H_2O	0.24	0	1.35	1.58	0
CH_3OH	0	$<$0.01	$<$0.01	$<$0.01	0.09

5 Yulin Coal Chemical carbon capture project

5.1 The coal to chemical facility

Shaanxi Yanchang Petroleum Yulin Coal Chemical Co. Ltd. (Yulin Coal Chemical) is a wholly owned subsidiary by Shaanxi Yanchang Petroleum (Group) Co. Ltd, and is located in Yuheng Industry Zone, Yulin City, Shaanxi Province. The facility covers an area of 136 hectares and employs more than 700 staff.

This facility is the first coal to chemical project invested by Yanchang Petroleum. It produces 1 million tonnes per year of acetic acid and other products. The investment amount was about RMB15.3 billion and the project was constructed in two stages. The first stage of construction was designed to produce 200,000 tonnes of methanol per year, and 200,000 tonnes of acetic acid per year. It is also equipped with low temperature methanol wash process.

The project uses the Texaco coal-water slurry gasification technology and low-pressure hydroxyl synthesis technology for acetic acid production. The project construction started in June 2007 and on 11 March 2011, it was commissioned and produced qualified methanol product.

5.2 Brief description of the process

This facility uses a low temperature methanol wash process for CO_2 capture, which is based on a similar principle as the aforementioned CO_2 removal process at Yulin Energy Chemical facility. Therefore, only a few key steps in relation to compression and liquefaction are briefly introduced in the following setions. To better understand the process, the process flow diagram for the compression and liquefaction is shown in Appendix Figure A-2 and the floor plan is shown in Figure A-3.

(1) The rich solvent from low temperature methanol purification equipment desorbs CO_2 by using a dedicated methanol carbon dioxide separator. Desorbed carbon dioxide is then compressed by the compressor, cooled and separated from the non-condensable gas, and finally liquid CO_2 with a purity ≥99% is obtained.

(2) The rich solvent from the bottom of separator will be pumped again into the pipeline 119 which contains sulphur-free medium-pressure rich solvent and will be returned into the H_2S concentrating tower T1603.

(3) CO_2 vapour from the top of separator V0001 will be eventually sent into compressor K0001 after passing through heat exchanger E0001 in which the cooling energy is recovered by the medium-pressure flash vapour in pipeline 126.

(4) The medium-pressure flash vapour for cooling energy recovery will be returned into pipeline 126 afterwards and then enters the feed gas pipeline 102.

(5) After being compressed in K0001 and cooled down in the water cooler E0002, CO_2 is pumped into the propylene cryogenic heat exchanger E0003 for liquefaction. Then the stream will enter CO_2 liquid-vapour separator V0002 where liquefied CO_2 product comes out from the bottom and vapour phase re-enters the capture process pipeline 147.

(6) The liquefied CO_2 product from the bottom of liquid-vapour separator V0002 flows into the cryogenic tank. A cryogenic pump will be used to pump the liquid CO_2 into cryogenic tank truck that is used to transport the CO_2 to the operating site when necessary.

The project was successfully commissioned and started producing qualified products in November 2012. The system is relatively simple with less use of rotating equipment. The ultimate CO_2 purity of more than 99% is achievable after compressing, cooling down and separating process. The composition of CO_2 product is listed in Table 3.

TABLE 3 Quality Index of Liquefied CO_2 Product

No.	Component	Content
1	CO_2: % (v/v)	≥99.50
2	H_2O: PPm (v/v)	≤20
3	Acidity: PPm (v/v)	qualified
4	Total Sulfur: PPm (v/v)	≤0.1
5	Oxygen: PPm (v/v)	≤30
6	Odour	No odour

6 Compression and transportation

6.1 Carbon dioxide compressor

With the development of China's economy, CO_2 compressor design and manufacture technologies have experienced a rapid development in China. Some technologies have reached international level. Nevertheless there are still certain gaps in several areas, compared with major international compressor manufacturers. Project proponents should choose economic, reliable, efficient and environmental CO_2 compressor and avoid problems such as machine maintenance and cost increase due to the model selection mistakes.

According to the difference of compressor structures, compressors can generally be divided into piston, centrifugal, screw and scroll rotor type. Screw compressors with suitable pressure range could work under high.

However, screw compressors are generally heavy and the discharge of gas may not be continuous. It may produce pressure fluctuation and vibration. Centrifugal compressor features large flow, high power rating and good efficiency, but it has the issues of high price, high air velocity and great friction loss. Furthermore, its efficiency is still lower than piston compressor, and the maintenance cost is high for such type of compressor.

A screw compressor is generally highly reliable and its operation and maintenance are less complex. It has the following advantages:

- Unattended operation
- Operation simplicity
- Outlet gas flow rate adjustable
- Good dynamic balance
- Small volume and footprint, light weight
- Smooth operation
- Small vibration
- Stable exhaust
- High efficiency over broad range
- Small number of parts, less consumable parts
- Long service life

However, it does have relatively high power consumption, and screw gaps get bigger after long period of operation which requires regular repair or replacement. Considering a variety of factors such as displacement capacity, efficiency, power consumption and cost, screw compressor was selected for Yulin Energy Chemical Project.

6.2 Carbon dioxide transport strategy

For the CCUS projects in the U.S. and other countries, CO_2 is mainly transported by pipeline. CO_2 pipeline construction began in the 1960s and in the early days, the pipeline was mainly used in CO_2 transport for enhance oil recovery (EOR). At present, there are more than 6,500 km of CO_2 pipeline length in the United States.[8]

Construction of CO_2 pipelines has only started in recent years in China but the scale is small with no commercial long distance CO_2 pipeline yet. Considering the topography and costs of building new pipelines, Yanchang Petroleum chose to source CO_2 from coal to chemical plant in close proximity to the oilfield for CO_2-EOR site. Yanchang Petroleum built 50,000 tonnes per year CO_2 capture plant in Yulin Coal Chemical facility and the plant was put into production in 2012. It transports high concentrations CO_2 produced from the plant to Jingbian oil field for CO_2 EOR and storage by twenty-ton tanker trucks. Compared with the previous CO_2 source from Xingping fertiliser plant which was used for testing before Yulin Coal Chemical Capture Project was commissioned, the transportation distance is now shortened from 500 km to 140 km which greatly reduced the transportation cost.

In order to further reduce CO_2 transport costs, the second CO_2 capture plant with 360,000 tonnes per year capacity is located in Jingbian County. After the capture plant is put into

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[8] Global CCS Institute 2014, *The Global Status of CCS: 2014*, Melbourne, Australia.

production, the CO_2 transport distance will be shortened to 10 km and transport costs will be reduced even further. This plant provides stable and affordable CO_2 sources for CCUS projects.

Considering the development of large-scale CCUS project, Yanchang Petroleum started the CCUS feasibility study for a 4 million tonnes per year project, which includes CO_2 pipeline feasibility study. The pipeline feasibility study would cover plant condition and general layout, pipeline network, route selection and economic evaluation. This would provide solid foundation for the deployment of large scale CCUS project by Yanchang Petroleum in the near future.

6.3 Technology choice for carbon dioxide transport

For transportation and injection, the CO_2 captured is usually transformed into liquid or supercritical state. Two approaches are considered for the transport of CO_2 by Yanchang Petroleum.

Approach 1

The captured high concentration CO_2 (98mol%, temperature: 21°C, pressure: 0.04MPag) goes through a multi-stage compression to reach the pressure of 3.0MPag where water will be removed and CO_2 is cooled and liquefied by refrigerant. The liquid then goes through a throttling-expansion process to produce supercooled liquid. The CO_2 liquid（2.0MPag, -30°C）is stored in tanks (sphere tank). Propylene is used as refrigerant agent. The process is as follows:

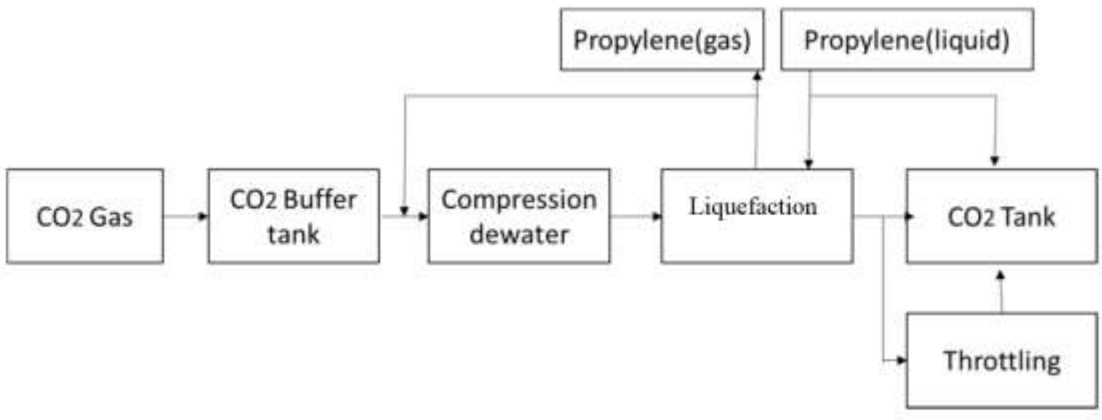

FIGURE 3 Principle flow diagram of Approach 1

Approach 2

The captured high concentration CO_2 (98mol%, temperature: 21℃, pressure: 0.04MPag) goes through a multi-stage compression to reach supercritical state (15.0MPag，50°C) directly. Water is removed during the process and the supercritical CO_2 is then transported to the users (injection well).

Yanchang Petroleum analysed and compared the two approaches. Approach 2 requires more upfront investment to build pipeline, but its process chain is simpler and transportation costs are lower. The disadvantage of Approach 2 is that there is no engineering precedent in China. The lacking of physical data and engineering experience of handling supercritical CO_2 are unfavourable for supercritical pipeline transport approach. Therefore, the recommended technology choice for the project is Approach 1. CO_2 is liquefied and transported by cryogenic tank trucks.

6.4 Liquefaction and compression of carbon dioxide

The feed gas is sourced from Yulin Energy Chemical facility. This plant emits CO_2 at a rate of 23,000Nm^3/h (assuming 8,000 hours a year, total volume may reach 360,600 tonnes per year). Therefore, the CO_2 capture plant has a designed capacity of about 360,000 tonnes per year.

General principle

At present, the common way to produce liquid CO_2 is to increase its liquefaction temperature by compression and then CO_2 is refrigerated and liquefied by the refrigerant from cryogenic cycle.

Compressor and freezer

The maximum capacity of single train compressor is about 300,000 tonnes per year for CO_2 compressors made in China. The maximum capacity of single screw freezer is about 200,000 tonnes per year. In order to get a better match for the CO_2 compressor, a single freezer with capacity of 180,000 tons/year is selected. At the same time, the single train compressor with the capacity of 180,000 tonnes per year is selected, which takes into account the feed gas supply stability and maintenance requirements. Therefore, the 360,000 tonnes per year plant will comprise two production trains, each with a capacity of 180,000 tonnes per year.

Refrigerants

There are two types of refrigerants generally used by industry, propylene and ammonia. The propylene produced by Yanchang Petroleum is used for this project as the cryogenic cycle has large capacity and lower energy consumption. In the cryogenic cycle, propylene goes through four steps, including compression, condensing, throttling expansion and heat transfer. This process provides cold energy for liquefying carbon dioxide. Another reason for using propylene is that the engineers and project managers are familiar with the use of propylene as a refrigerant. A steam turbine is used to compress the propylene. By using the same refrigerant for the carbon capture process and the CO_2 compression, the overall process is simplified and significant cost savings are achievable.

Process description

The main equipment includes: compressor, liquefaction and refrigeration system, storage and filling system. The CO_2 feed gas from the coal to chemical plant is transported into this unit through pipeline. First, the feed gas enters into V-101 buffer tank, and is then compressed by two C101A/B compressors to 3.0MPag，40°C. Compressed CO_2 gas enters the E-101A/B condenser and condensed CO_2 will be liquefied by refrigerant propylene at about -13°C, 2.95 MPa.g. Flowing out of the CO_2 condenser，liquid CO_2 enters spherical tank for storage. For transport，liquid CO_2 is pumped into a tank truck through pump P-102A-F. Product CO_2 quality requirement and the compression inlet gas conditions are listed in Table 4 and 5 respectively.

TABLE 4 Liquid CO_2 quality index for EOR

No.	Project	Index
1	Volume friction of CO_2/%，≥	90
2	Volume friction of water/%，≤	0.1
3	Volume friction of total sulphur/%，≤	0.001
4	Volume friction of hydrocarbon（methane）/%，≤	0.3
5	Temperature (transportation, storage)	-20℃
6	Phase	liquid

TABLE 5 Compression inlet gas conditions

Project	CO_2 feeding gas（beyond water tower）V%
H_2	0.0435
N_2	0.3305
CO	0.7675
AR	0.0033
CH_4	0.0135
CO_2	98.804
eH_2S	0.00008（max0.000162）
COS	0.0005
CH_3OH	0.0369
H_2O	0.00002
HCN	0.00003
Temperature（℃）	31
Pressure（MPaA）	0.179

7 Site layouts

Layout of CO_2 capture plant at Yulin Coal Chemical

Transmission equipment and purifiers are located in the highlighted framework (no fences around the framework), and the rest are arranged in the open area (Fig. 4). It covers an area of about 1,500~2,000 m^2.

Layout of CO_2 capture plant at Yulin Energy Chemical

The project covers an area of 16,150 m^2, wherein the east-west length is 95 m and the north-south is 170 m (Figure 5, Appendix A-4). The area can be divided into management area, production area, storage area and the loading area. Some major technical parameters are:

- 360,000 tons/year CO_2 plant;
- Reserved land for stage two:
- Tank area 1: three 2,000 m^3 spherical tanks
- Tank area 2: reserve area for three 2000 m^3 spherical tanks
- Loading area: build six new loading docks and reserve two docks.

FIGURE 4 Picture of CO2 capture plant for Yulin Coal Chemical

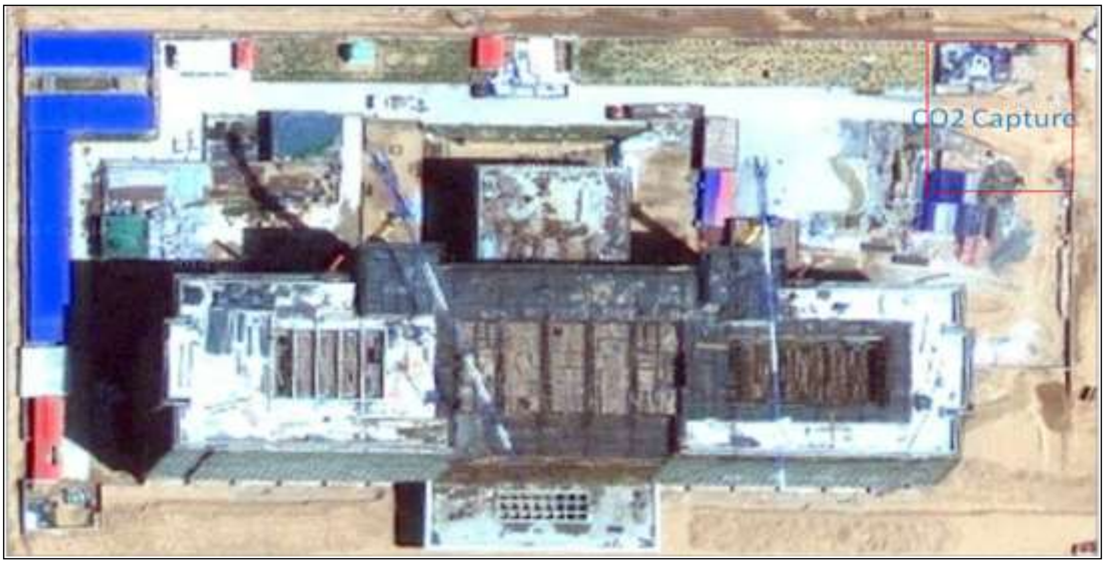

FIGURE 5 Location of CO2 capture plant of Yulin Energy Chemical

8 Project timeline

To better share the project management experiences and lessons learned, key events of the two projects are included in the following tables.

TABLE 6 Yulin Coal Chemical CO_2 project schedule

Date	Key Project Milestones
September 2010	Feasibility
January 2011	Front End Engineering Design(FEED)
May 2011	Project Final Investment Decision(FID) made
December 2011	Detailed Design completed
March 2012	Equipment procurement
June 2012	Site civil work completed
September 2012	Installation completed
November 2012	Commissioning completed
December 2012	Operational

TABLE 7 Yanchang Yulin Energy Chemical CO_2 project schedule

Date	Key Project Milestones
September 2014	Feasibility
September 2015	Front End Engineering Design(FEED)
December 2015	Project Final Investment Decision(FID) made
March 2016	Detailed Design completed
June 2016	Equipment procurement
August 2016	Site civil work completed
December 2016	Installation completed
February 2017	Commissioning completed
March 2017	Operational

9 Commercial drivers

The success of Yanchang Petroleum CCUS Project depends on macro and micro level factors. These factors will be discussed in the following section.

Macro level: the national strategy of energy conservation and emissions reduction; international cooperation

In order to reduce CO_2 emission, the Chinese Government proposed that the CO_2 emission intensity of GDP in 2020 be reduced by 40%-45% compared to 2005 levels.[9] CO_2 emission from coal to chemical industry is projected to be around 470 million tonnes per year in 2015.[10] How to economically manage CO_2 emission from coal to chemical industry is a well-known global issue. In response to national energy strategy and national energy conservation and emissions reduction policy, Yanchang Petroleum established the CCUS strategy based on

[9] China National Development and Reform Commission 2012. *China's National Plan on Climate Change for 2014-2020.* Paris.

[10] Hu. J 2013. '2015 Coal chemical carbon emission is expected to reach 470 million tonnes '. *China Energy Newspaper*. 11 November. p.2.

considerations for its coal chemical industry development and current status of oil/gas production. The government's direct support is a critical factor, and has provided funding for this project.

Additionally, Yanchang Petroleum also has received substantial international support. The Global Carbon Capture and Storage Institute has supported this project and aims to promote sharing of the knowledge and experience from this project. Chinese government supported Yanchang Petroleum to cooperate with the university and research institutions from America and Canada.

Yanchang Petroleum has undertaken series of important projects, such as "CO_2 EOR Technology Research in Yanchang Petroleum", "CO_2-EOR Pilot Test in the Demonstration Area", "CO_2 Geological Sequestration Evaluation", "CO_2 Capture, Sequestration and EOR Technical Demonstration for North Shaanxi Coal Chemical Industry".

Micro level: improvement of oil production by EOR

From the microeconomics perspective, CO_2-EOR is an efficient way to exploit low permeability reservoirs and it is also the key to increase revenues for oil corporations.

Yanchang Oil-field is located in Ordos Basin, characterised by low and ultra-low permeability reservoirs with huge potential for CO_2-EOR and CO_2 sequestration. Coal to chemical industry is booming and high concentration CO_2 resource is abundant. Coal to chemical industry will provide CO_2 for Yanchang CCUS project while the benefit from EOR promotes the work for CO_2 capture, transport and storage.

The proven geological oil reserves of Yanchang Petroleum are about 2.25 billion tonne and 1.76 billion tonnes is suitable for CO_2-EOR. By estimation, about 400 million tonnes CO_2 may be permanently stored. CO_2-EOR can improve the oil recovery by 5%-10%, while the recoverable reserves are increased by about 85 to 176 million tonnes. Yulin Energy Chemical project may provide stable CO_2 supply for Yanchang CCUS Project to utilise and store CO_2. Yanchang Petroleum have conducted a detailed analysis regarding the economic benefit of this project at the feasibility study stage. The data and analysis are described below.

As an advantage, the carbon capture unit (low temperature methanol wash process) is an essential part for a coal to chemical industry process. It may be difficult to estimate the cost for CO_2 capture project alone. The total investment of the project is RMB26.59 million (the feed gas cost is not included). Furthermore, the policy benefits are not considered, because there is no carbon tax or carbon trading market in Shaanxi Province at the moment.

From Table 8, it can be seen that electricity consumption is the main cost for CO_2 compression. With equipment depreciation calculated over ten years, the cost of liquid CO_2 production is estimated at RMB117.35/t (US$18.897, assuming 1USD=6.21RMB). The cost is much lower than CO_2 captured from post-combustion power plant and the low cost of CO_2 is the key commercial driver for this project.

TABLE 8 Cost Estimation for one tonne Liquefied CO_2 Product

No	Item	Unit	Consumption	Price（Yuan）	Unit Cost（Yuan）	Remark
1	Feed Gas	Nm^3	800	0.00	0.00	-
2	Electricity	Kwh	80	0.65	52.00	-
3	Desalted Water	t	0.1	10	1.00	-
4	Circulating water	t	25	0.12	3.00	-
5	Liquid Nitrogen	kg	0.10	25	2.5	-
6	Instrument Air	Nm^3	30	0.10	3.0	-
	Subtotal	**-**	**-**	**-**	**61.5**	**-**
7	Depreciation	-	-	-	50.52	10 years of depreciation, residual value rate is 5%
8	Maintenance	-	-	-	2.526	0.5% of Depreciation
9	Labour Wages	-	-	-	2.80	2 Persons，50,000 Yuan/Year
	Total	**-**	**-**	**-**	**117.35**	**-**
Remark：Total Investment RMB26.59 million.						

Using the same method, the cost of the CO_2 capture project in Yulin Energy Chemical Company is approximately RMB132.66/t as shown in Table 9.

TABLE 9 Cost estimation of liquid CO_2 for Yanchang Petroleum Yulin Energy Chemical

No	Project	Unit cost （Yuan）	Note
1	Material cost	0	-
2	Auxiliary materials cost	0	-
3	Outsourcing fuel and power cost	81.16	-
4	Labour and welfare expenses	3.16	-
5	Manufacturing cost	45.79	-
5.1	Depreciation for plant assets	39.49	depreciation of 12 years, remaining value of 3%
5.2	Repair cost	1.04	3% of plant assets
5.3	Other manufacturing cost	5.26	-
6	Sales cost	2.55	1% of sales revenue
Total		**132.66 Yuan**	

CO_2 produced is utilised for EOR. Assuming that 4 tonne CO_2 produces 1 tonne crude oil, the EOR economic benefit is estimated as shown in the Table 10.

TABLE 10 EOR economical benefit calculation

Item	Amount		
Liquid CO_2 unit cost, US$/t	18.897		
CO_2 cost for transport, US$/t	12.882 (Assuming a distance of 50 km, CNY1.60 per tonne per km)		
CO_2 total cost (transported), US$/t	31.779		
Assumed CO_2 amount for producing oil, t/t	4.0		
Unit oil price per barrel, US$/b	64.08* (assuming RMB 3000/t)		
Oil unit conversion barrels per tonne, b/t	7.333		
Oil price per tonne, US$	469.89864		
CO_2 cost per tonne oil, US$	127.08		
CO_2 amount required per barrel oil, t/b	0.5457		
CO_2 cost per barrel oil, US$/b	17.34		
Sensitivity			
Assumed other exploration cost and tax per barrel oil, US$/b	20.00	25.00	30.00
Total cost per barrel oil, US$/b	**37.34**	**42.34**	**47.34**

Note: The Brent crude oil price is assumed to be US$64.08/b (as per April 28, 2015).

Based on the simplified calculations and assumptions, it can be seen that CO_2-EOR may have a certain profit margin even without the benefits from a carbon trading market. Clearly the international oil price fluctuations would have an impact on the profitability of CO_2-EOR project. Within certain oil price range, this project may still have a relatively good Internal Rate of Return (IRR) making the project commercially feasible. Furthermore, Yulin Energy Chemical could reduce its net CO_2 emission by permanent CO_2 storage. Therefore, the project may produce significant economic and social benefits.

In summary, national policy for energy conservation and emission reduction, active and effective international cooperation, sustainable development prospect of CCUS, considerable economic benefits, mature advanced capture and purification technology and advanced project management model have all played vital roles in the project decision-making process.

10 CO_2 emissions and capture efficiency analysis

10.1 CO_2 emission analysis of Yulin Coal Chemical Company

The project construction started in June 2007 and it successfully produced the qualified methanol product in March 2011. Table 11 presents the production capacity and CO_2 emission. Currently, 52,000 tonnes CO_2 per year can be captured for CO_2-EOR and storage in this project. This means that carbon emission of the project could be reduced by more than 30,000 tons.

TABLE 11 Production capability and CO_2 emission load for the first Stage

Product	Production capability （tonnes/year）	Coal consumption (tonnes /year）	CO_2 emission （tonnes /year）	High concentration CO_2 emission （tonnes /year）
Methanol	200,000	440,000	400,000	52,000

10.2 CO_2 emission analysis of Yulin Energy Chemical

Yulin Energy Chemical accommodates a large coal to chemical, gas to chemical and oil to chemical integrated facility for the production of polyethylene and polypropylene. Table 12 shows the production capacities and CO_2 emissions. With the operation of the CCUS project, the amount of CO_2 captured is 360,000 tonnes per year and carbon emission could be reduced by more than 180,000 tons per year if it is used for CO_2-EOR and storage.

TABLE 12 Production capability and CO_2 emission load of Yulin Energy Chemical

Product	Production capability （tonnes/year）	Coal Utilisation (tonnes/year）	CO_2 emission （10^4 tonnes/year）	High concentration CO_2 emission （tonnes/year）
Methanol	180,000	3,960,000	3,600,000	360,000

10.3 Capture efficiency

Capture efficiency is an important parameter for evaluating capture technology. Carbon capture efficiency can be calculated with many methods. For power plant capture process, CO_2 capture efficiency could be calculated by comparing theoretical capture amount with its actual capture amount because there are three gas streams involved for such calculation (flue gas, CO_2, and cleaned flue gas). For coal to chemical process, the calculation may be complex.

The capture process gas streams include raw syngas, CO_2 product gas, purified syngas and tail gas which all contains CO_2. Two methods are used to calculate CO_2 capture efficiency.

i. Capture efficiency = actual CO_2 captured /theoretical methanol solvent absorption capacity

ii. Capture efficiency = actual CO_2 captured/total CO_2 amount in raw syngas

The actual working efficiency of the solvent can be calculated with first method while the CO_2 capture rate of the entire system can be measured by the second method. Based on the two methods, the CO_2 capture efficiency is calculated for the two projects.

For Yulin Coal Chemical capture process, the interface for CO_2 compression/liquefaction process and coal to chemical process is located at the pipeline of sulphur-free medium pressure rich solvent, which has a mass flow rate of about 119,400 kg/h. The liquid CO_2 production rate is 8.36 tonnes per hour and the composition of the rich solvent is listed in Table 13. The CO_2 capture efficiency is then calculated as 26.13%.The unit operates steadily in the range of 80-120% load, with the maximum designing load of 120%. The continuous time for operation is 8,000 hours per year.

For Yulin Energy Chemical Company carbon capture unit, the CO_2 amount in raw syngas is 50,649.2 Nm^3/hr and CO_2 captured is 22,650.0 Nm^3/hr. The capture efficiency may be calculated as 44.719%.

TABLE 13 Major Components of Methanol-Rich Solution

Components	H_2	N_2	CO	AR	CH_4	CO_2	H_2S	COS	CH_3OH	H_2O
mol%	0	0	0.001	0	0	0.21	0	0	0.788	0.001

11 Achievements and experiences

Yanchang Petroleum Group is located in the North West China, which is traditionally a less developed area. Project staff generally have less experience managing large projects and may be more or less influenced by some traditional cultures and customs.

This project has a tremendous scope involving complex processes and numerous tasks. The staff on the project have found it challenging at times and there had been conflicts due to the differences of values and cultures.

The project experiences are discussed below.

i. Close proximity of source and sink provides solid foundations for CCUS project.

If a CCUS project is in operation at the coal-chemical industry near the Ordos basin, the project can get lower cost CO_2 than power plant and lower transportation cost due to the short distance from capture sites to injection sites. Accordingly, the CO_2-EOR operation can achieve more economic benefits. CO_2-EOR may be an efficient pathway for China to start CCUS project in the coal to chemical industry near the major oil/gas basins.

ii Novel coal to chemical process could achieve significant emission reduction.

Compared with direct coal liquefaction, the specific capital expense (dollar per ton per day oil) for oil-coal co-processing is reduced by more than 50%, while oil yield increases from 50% to more than 75% and the CO_2 emission was reduced by approximately 50%. The coal conversion rate can reach 90% and energy consumption per ton oil is reduced by more than 15%. The coal to chemical project optimises the utilisation of low-rank coal and heavy residual oil. Such process is characterised by high production yield, low energy consumption and remarkable economic and social benefits.

iii. It is important to select and make the best use of existing proven technology.

The project team did not make many modifications to existing commercial carbon capture technologies. The capture process takes full advantage of low temperature methanol wash and it has relatively simple process flow, requiring less equipment, smaller investment and lower operating costs.

iv. Advanced project management model is important for the implementation of large scale CCUS project.

For this project, Yanchang Petroleum cooperated with a famous international project management company and adopted the Integrated Project Management (IPMT) model. Yanchang Petroleum achieved significant learnings about the management of large projects, and accumulated valuable experiences.

For the implementation of the project, an advanced management model, Engineering Procurement Construction (EPC) was introduced. Although a surprising finding for many, the E+P+C model is used widely in China, which usually requires three separate contracts for engineering, procurement and construction. For E+P+C, the project management is often disordered due to the lack of lead project management. Time management are often poor under the traditional model. The integration and coordination between different units/modules are difficult and often leads to issues, especially during the commissioning process. Under the traditional model, the engineering construction and the training of staff operators are not well coordinated which may result in lower work efficiency and higher operation costs.

All these issues can effectively be avoided/handled with the EPC model. There are two key learnings regarding the new EPC model. The first one is the improvement of values, which is a great progress for both Yanchang Petroleum and for coal to chemical industry in China as a whole. The second point is that the improvement of management skills is a breakthrough for the enterprise culture of Yanchang Petroleum.

v. CCS-readiness requires forward planning and strategic thinking.

Building in CCS in the early stages of planning should become part of the strategy for coal to chemical industry.

Yanchang Petroleum made a strategic decision at the planning stage of Yulin Energy Chemical facility and included dedicated equipment to increase the CO_2 concentration to more than 99% (up from 80%). However, if Yanchang were to add such units from scratch today, such as special layout, pipeline construction, existing unit modification, it would be more difficult and more expensive.

Regarding the pipeline transport, the pipeline corridor reserved 30% space for CO_2 pipes at the planning stage. Such strategic reservation makes current expansion of CO_2 capacity and future increase possible and economical. It is always easier to plan things well at the very beginning as it may be difficult to retrofit existing equipment later on.

For traditional low temperature methanol wash process, CO_2 product tower is not included and the CO_2 absorbed by methanol is desorbed in the H_2S concentrating tower. In this project, process optimisation was implemented and a dedicated CO_2 product tower was designed and included which desorbed CO_2 of high concentration. For the purpose of meeting CO_2 quality requirements for EOR, there is no need to modify the methanol wash plant. After all, any modification to a traditional low temperature methanol plant is difficult. The design of this project makes the downstream processing of CO_2 easier. CO_2 just needs to be compressed and liquefied requiring minor modifications to the existing plant and very small land area.

Furthermore, it is important to have strategic planning of the power requirement for CO_2 compression and transportation. The power supply for the entire coal chemical plant was designed at 300MW even though the coal chemical process itself only requires 200MW. The reserved power capacity would meet the power demands of large CCS projects. Power reservation shall be another aspect of CCS-readiness for coal to chemical project. Such planning will again save costs and time for CCS project. Yanchang Petroleum also proposed the new idea of the combination of coal chemical and distributed power generation, which utilises the heat and cold energy in the coal to chemical process to generate power. Such approach achieves effective utilisation of resources and reduces carbon emissions.

To some extent, Yanchang Petroleum's forward thinking and planning constitutes CCS-readiness. The Yanchang model could be used by other coal chemical project developers in terms of CCS-readiness technical standards.

vi. Energy and climate change policy and strategy are important.

The CCUS project is an important technology for Shaanxi province to reduce its carbon emission and increase oil gas reserves and productions. It complies with China's national energy and environmental strategy. Oil production can be increased through CO_2-EOR project which brings economic benefits to the company. The deployment of CCUS can boost local employment, promote industry development and generate other social benefits. All the aforementioned factors have contributed to the success of the CCUS project.

vii. Sufficient quality staff training are needed.

Among the onsite operators for this project, 98% hold the Bachelor degree, and all onsite staff have undertaken extensive training for at least two to three months to ensure that the operators have good understanding of the process, routine operation of the process and handling of simple technical outage. It was observed that the engineers and technicians onsite are very familiar with the process parameters. Adequate training is essential for the smooth operation of the process.

viii Specifications of CO_2 product quality shall have certain flexibility.

Designed CO_2 product purity should be flexible to meet different vendor's requirements. For example, the purity requirements for CO_2-EOR and for fertiliser are clearly different. Yanchang Petroleum discussed the issue with the technology supplier at the planning stage and as a result, the process was tailored and optimised to have lower energy consumption while maintaining product supply flexibility enabling the company to make the best use of the process.

ix Transportation mode selection should consider the actual local conditions.

Based on the geographic features of northern Shaanxi plateau, transportation cost is RMB1.60t/km and CO_2 transport need is less than 50t/h (based on annual amount of 360,000 tonnes per year). Using pipeline to transport CO_2 at supercritical state is an appropriate way for large CCS project, but for this project, further discussions and investigations are needed regarding the final decision of transportation method.

Another key issue of CO_2 transportation in China is that CO_2 is classified as dangerous goods under the current China work safe regulations (compressed or liquefied CO_2, No. 642).[11,12] This imposes significant higher burden on the transportation and storage of CO_2. The future large scale deployment of CCS technology requires the re-consideration of CO_2 by the State Administration of Work Safety and other government departments.

x. The timing of technical licensing could be very important.

Coal to chemical process comprises many operation units and equipment, such as air separation, coal gasification, CO_2 capture, special equipment (i.e. spiral tube heat exchanger), methanol synthesis, polyethylene and polypropylene production. Yanchang Petroleum signed technical license agreements with several technology vendors. The negotiation of these agreements took place during the 2008 Global Financial Crisis and as a result, Yanchang Petroleum was in an advantageous position in the negotiations and achieved significant license fee savings. Therefore, the appropriate selection of technology license would be a significant factor for overall project cost.

12 Risk analysis

Investment Risk

The upfront capital investment for CO_2 capture, compression and transport in coal to chemical industry may be substantial. The length of investment return period depends upon the economic benefits from CO_2 injection. Long term, stable support for CO_2 storage is vital for the reduction of investment risks. Furthermore, the lack of experiences in managing and operating large scale integrated CCS projects is another risk factor. The deployment of CCS demands large scale demonstration project for the purpose of accumulating experiences and cost reduction.

Technical Risk

CO_2 may be released from the sulphur-free medium pressure rich solvent. The process itself has certain technical risks and it imposes high requirements on material safety and duration. The low temperature handling and cryogenic storage of high purity CO_2 demands high standards for the equipment and technology.

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[11] The State Council 2011. *Regulations on the Safety Administration of Dangerous Chemicals*. Beijing.

[12] State Administration of Work Satety 2015. *Catalogue of Dangerous Chemicals* (2015 revision). Beijing.

CO_2 Product Storage Risk

The high purity CO_2 product are in cryogenic liquid form. There are certain technical requirements that need to be met in terms of storage vessel and the storage venue. It is important to prevent the risk of CO_2 leakages due to external environment changes.

In summary, the captured CO_2 will be mainly used for CO_2-EOR and storage at Yanchang Oilfield. If CO_2-EOR pilots cannot generate expected economic benefits or the EOR implementation plan cannot be realised in the near terms, there is a risk of relevant units being shut-down or running at half capacity which would be considered as a failure of investment.

Acknowledgements

This work was financially supported by Global Carbon Capture and Storage Institute. We thank Dr Tony Zhang and Dr Qianguo Lin for their constructive suggestions.

Appendix List of drawings

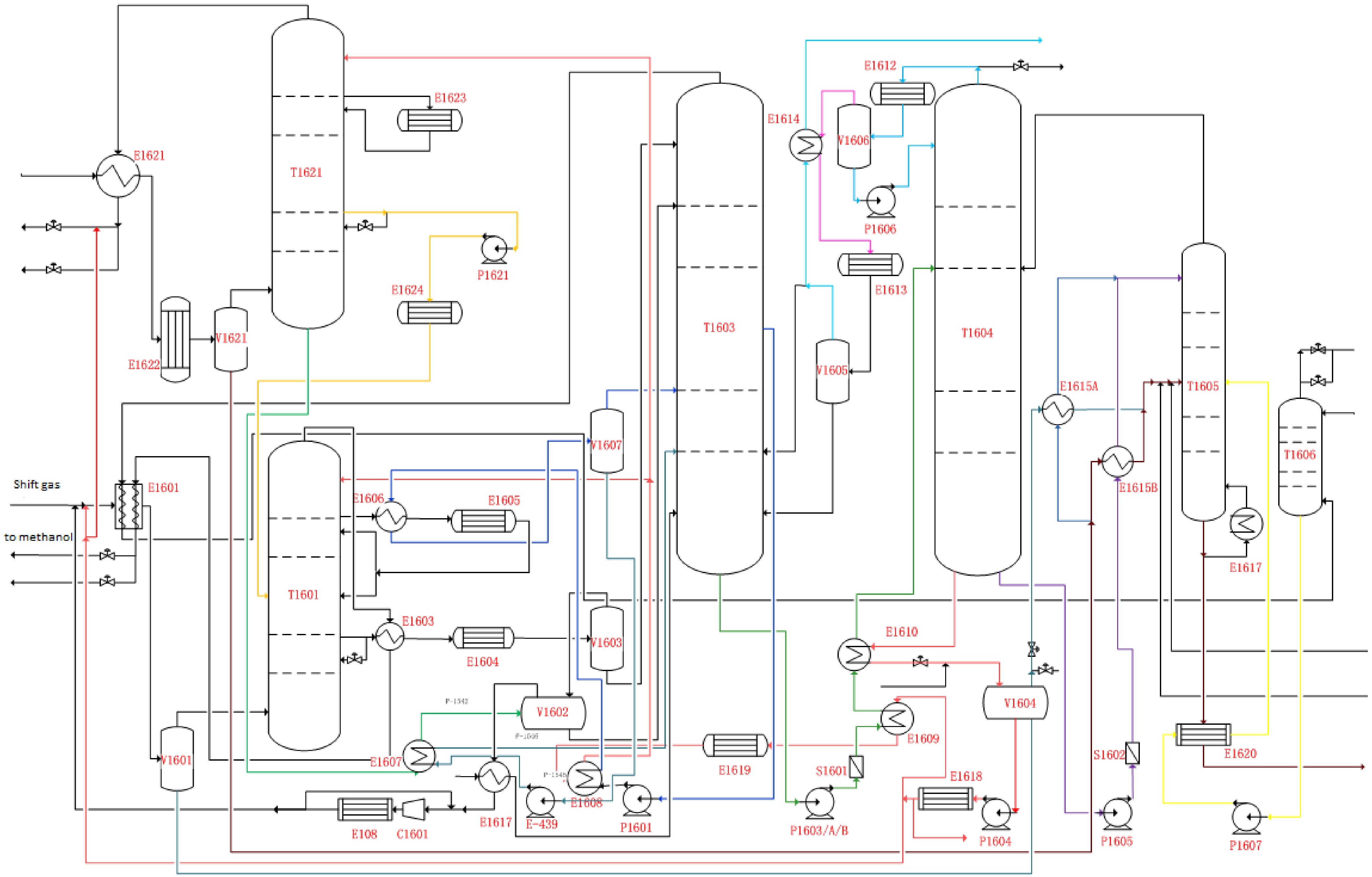

FIGURE A-1 Process Flow Diagram of Yulin Energy Chemical capture process

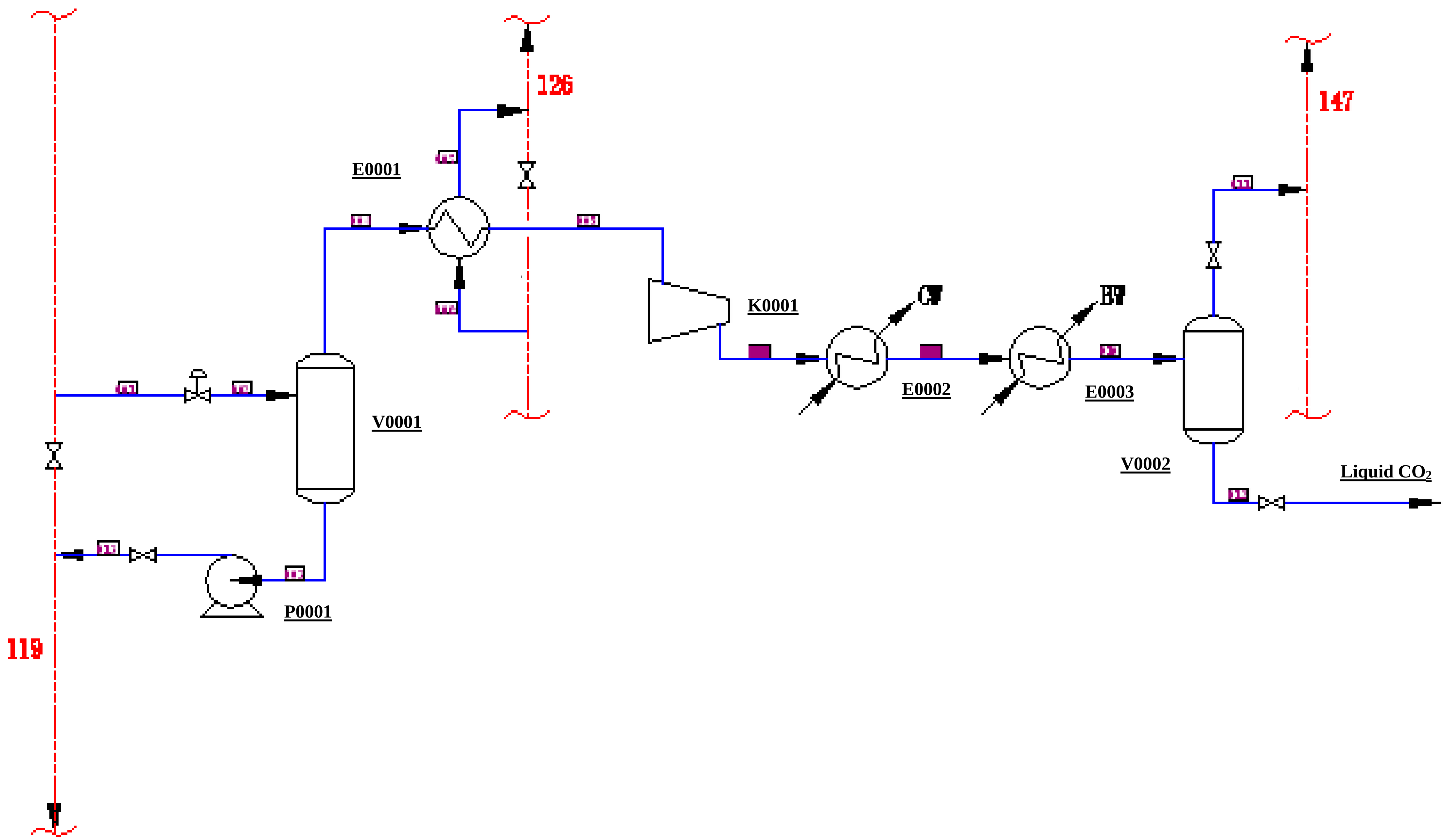

FIGURE A-2 Process flow diagram of Yulin Coal Chemical CO_2 compression and liquefaction

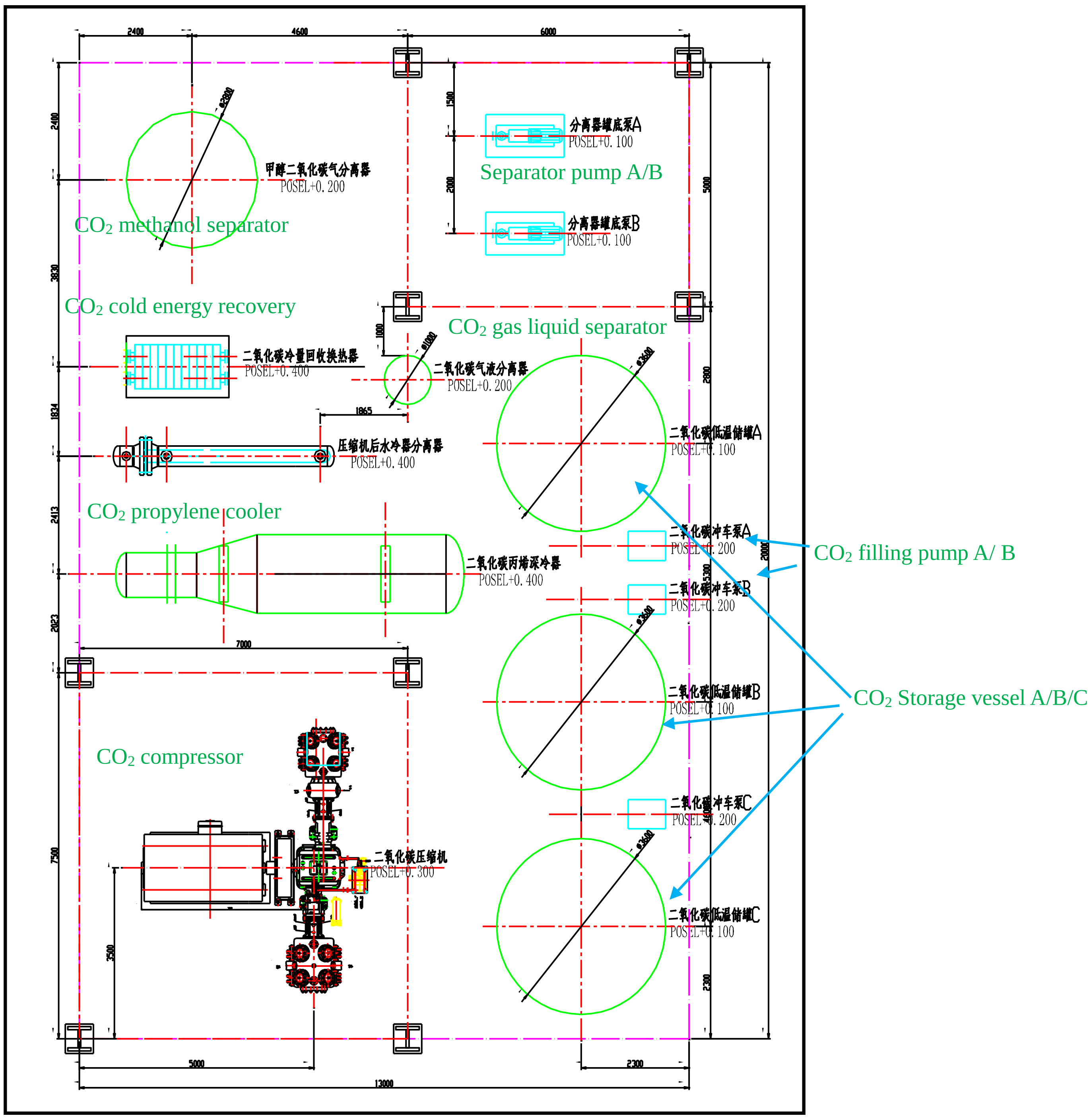

FIGURE A-3 General layout of Yulin Coal Chemical CO_2 compression and storage

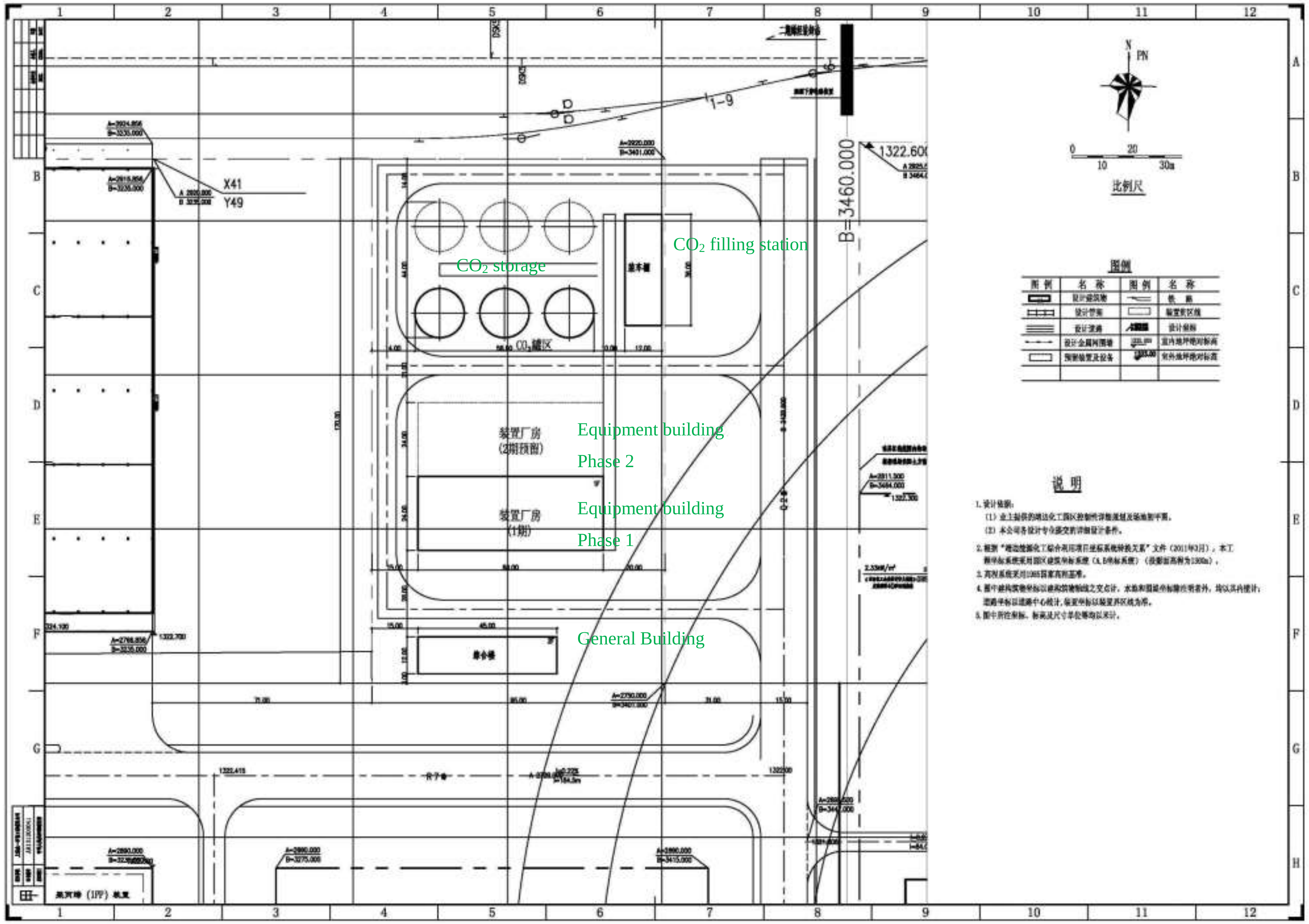

FIGURE A-4 General layout of Yulin Energy Chemical Capture Plant