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Supporting early Carbon Capture Utilisation and Storage development in non-power industrial sectors, Shaanxi Province, China

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Carbon capture and storage in non-power industrial sectors

Shaanxi Province, China

Carbon capture and storage (CCS) is a technology that can prevent the release of large quantities of CO_2 into the atmosphere from the use of fossil fuels in power generation and other industries by capturing CO_2, transporting and then pumping it into underground geologic formations to securely store it away from the atmosphere. Crucially, and why it is worthy of research, is the fact that CCS is a potential means of mitigating the contribution of fossil fuel emissions to global warming.

In the context of these reports, Carbon Capture Utilisation and Storage (CCUS) refers to the matching of industrial high-purity CO_2 sources, such as those of fertiliser plants or coal-to-liquid fuels facilities, with a sink industry which would make beneficial use of the captured and transported CO_2, such as Enhanced Oil Recovery (EOR). The capture of CO_2 from industrial high-purity sources requires much less additional process development than conventional carbon capture from the power generation industries because the production of pure CO_2 is already an inherent part of the process, often arising from gasification technology. Similarly, the sink industries may require less development than conventional CO_2 storage in geological formations like saline aquifers; hence, CCUS does not refer here to conventional carbon capture and storage.

CCS and China: the rationale for Shaanxi Province

CCS is an important technology for China to reduce its carbon emissions, while at the same time satisfying its increasing demand for electricity and chemical products and its continued reliance on coal. Shaanxi province in Central Mainland China is a region that has abundant fossil fuel resources of coal, natural gas and crude oil and has been ranked third in China for the production of these. It is also listed as one of China’s low carbon demonstration provinces. However, as a western and underdeveloped province, its energy structure is dominated by coal and heavy chemical production is still an important pillar industry in promoting economic growth.

CO_2 emissions of Shaanxi Province mainly derive from the consumption of fossil fuels. In 2005, they were 138 million tons and accounted for 2.4% of China’s total emissions. Thermal power plants are the main source of CO_2 emissions in Shaanxi Province, accounting for about 70% of the total; this is followed by the cement industry, accounting for about 10%. In addition, ethylene and synthesis ammonia industries account for about 10% and hydrogen production industry accounts for around 0.7%. According to preliminary measurements and estimates, CO_2 emissions from fossil fuels in Shaanxi Province had risen from 138 million tons in 2005 to 209 million tons in 2009, and before 2015 they may reach 450 million tons. In the coal chemical industry, CO_2 emissions are expected to reach 180 million tons by 2015. This is due to high energy-consumption in this industry, the associated large CO_2 emissions and the constant development of large-scale coal chemical projects for the future.

The implementation of early CCUS demonstrations in Shaanxi Province is of great significance. Firstly, Shaanxi Province urgently needs low carbon technology and CCUS is good for encouraging and developing this. Secondly, the chemical industry in Shaanxi Province is developed and has high-purity CO_2 sources. This can reduce the implementation cost of CCUS in Shaanxi Province and is good for promoting wide scale CCS deployment. Moreover, the Shaanxi provincial government holds a positive attitude to a CCUS project. Implementing early CCUS demonstrations in Shaanxi Province can help to build the image of Shaanxi as a clean energy province.

The current state of technology

To date a number of separate preliminary pilots for the capture and storage of CO_2 have been and are being undertaken in China. However, none of these pilots have succeeded in cost-effectively establishing a fully integrated CCS chain, due to insufficient coordination between capture and storage sectors.

Early demonstration of cost-effective CCUS potential in selected sectors can significantly advance CCS development in China in selected industries, in time crossing over into other sectors, including power, as the technology and policy conditions mature.

By directly engaging stakeholders from relevant industries and the EOR sector, this project explores carbon capture potential and the cost in these industries, and helps the National Development and Reform Commission (NDRC) and the Ministry of Science and Technology (MOST) in identifying and better coordinating potential CCUS early stage demonstration projects, while building awareness in these industries about potential opportunities for collaboration in CCUS.

There have not yet been any fully linked CCUS demonstration projects in Shaanxi. However, the Yulin natural gas chemical company employed CO_2 capture equipment in their facilities from 2004-2010. Research and Development on low carbon technology has been conducted in Shaanxi province since 2004 and the academic community and government agencies have held numerous seminars and published many papers and reports on the topic.

Objectives of these reports

The major objective of this work is to promote early opportunities for CCUS using high purity non-power industrial sources of Shaanxi, which may act as a catalyst for the larger scale deployment of the technology. A number of actions have been taken in support of this.

A review of the technical, policy, legislative and economic gaps and barriers relating to CCUS implementation in Shaanxi was conducted and reported, including; the identification of the funds to support the CCUS demonstration; difficulty in coordination of the whole CCUS chain covering different industries; and lack of government coordination through industrial policy, regulations and incentive policies will result in prohibitively high cost of initial CCUS demonstration projects and is likely to delay further development of potentially cost-effective CCS projects in China.

The identification of a suitable CCUS demonstration project in Shaanxi Province would help to promote the wider deployment of low carbon technologies. To do this, inventories of suitable high purity industrial CO_2 sources and CO_2 sink industries of EOR and Enhanced Coal Bed Methane (ECBM) have been compiled. The information has been gathered from a combination of industry surveys and publicly available information in academic papers, reports and on the Internet.

Based on a set of selection criteria and points system a number of potential CO_2 source-sink matches for a CCUS demonstration project were then identified. During the course of the project a number of workshops were organised with attendance of relevant stakeholders from CO_2 source and sink industries and local government. The workshops brought together the involved parties thus facilitating dialogue on promoting CCUS and were used to disseminate the project findings.

An examination of the potential of the oilfields and high purity CO_2 source industries located in Shaanxi Province in hosting an early opportunity CO_2 capture and utilisation demonstration project has also been considered and as a whole, the combination of these five reports provides a comprehensive overview of the carbon capture and storage potential in non-power industrial sectors in Shaanxi Province.

Recommendations

Based on the findings of this project we submit the following recommendations for the development of cost-effective early CCUS opportunities in China:

1. Officially adopt a China CCUS roadmap provide the policy framework for developing detailed policies and regulations to enable larger and more CCUS demonstration projects. Prioritise concentrated high-purity CO_2 sources and EOR as target sectors for CCUS development in the medium term.
2. Support R&D activities on high-purity CO_2 capture, transportation and EOR as part of the National Future Science Development Plan. Such R&D activities will contribute to minimising project risks and improving effectiveness throughout the CCUS chain. It is recommended that strong emphasis is put on EOR, as the further development of EOR technology and capabilities in China will help define the value of CO_2 for EOR as a primary driver for developing the CCUS chain. Existing R&D funding mechanisms under the 863 and 973 programmes of MOST may be used to support these activities.
3. Conduct detailed technical and economic feasibility assessments for the four identified full-chain CCUS projects in Shaanxi. Attracting investment in these projects will require the development of strong business cases with clearly identified technological, environmental, safety and economic risks to be allocated among the various stakeholders and the government. Detailed technical and economic feasibility studies are needed to ascertain these costs, benefits and risks.
4. Designate one high-purity CO_2/EOR project in Shaanxi as a national demonstration project to be implemented under the direct guidance and leadership of the NDRC, so that NDRC can coordinate the work of MOST, MEP and MLR from the national level down to the local level to ensure effective implementation of the project.
5. Develop CCUS demonstration funding mechanisms using government funds. Such funding mechanisms are required to address specific risks associated with large first-of-a-kind infrastructure projects such as full-chain CCUS projects and leverage finance from the parties in the CCUS chain. Possible financing mechanisms include low-interest loans, guarantees and direct government financing for public CCUS infrastructure such as pipelines.
6. Foster international collaboration on R&D, financing and development of demonstration projects. China already has extensive international collaboration in the field of CCUS. Such international collaboration can be leveraged to address specific knowledge barriers for developing CCUS demonstration projects and may also provide funding for CCUS project feasibility assessments in China.

Gaps and Barriers to Carbon Capture Utilisation and Storage in Non-power Industrial Sectors of Shaanxi Province, China

Supporting early Carbon Capture Utilisation and Storage development in non-power industrial sectors

1. Background and Introduction

1.1. CCUS and its significance to the Shaanxi Province, China

Carbon capture and storage (CCS) refers to the technology attempting to prevent the release of large quantities of CO_2 into the atmosphere from fossil fuel use in power generation and other industries by capturing CO_2, transporting it and ultimately pumping it into underground geologic formations to securely store it away from the atmosphere. It is a potential means of mitigating the contribution of fossil fuel emissions to global warming.

According to the state condition of China, the CCUS concept (carbon capture, utilisation and storage) is proposed. Based on CCS, the CO_2 utilisation process is added, including Enhanced Oil Recovery (EOR), ECBM, utilisation in the food industry etc.

Some definitions of CCS from different authoritative organisations are listed in Table 1.1

Table 1.1: Definitions of CCS

Organisation	Description
IPCC	In the approach of CCS, CO_2 arising from the combustion of fossil and/or renewable fuels and from processing industries would be captured and stored away from the atmosphere for a very long period of time.[1]
GCCSI	CCS is a technology to prevent large quantities of carbon dioxide or CO_2 (a greenhouse gas) from being released into the atmosphere from the use of fossil fuel in power generation and other industries. The technology involves: • collecting or capturing the CO_2 produced at large industrial plants using fossil fuel (coal, oil and gas); • transportation to a suitable storage site; • Pumping it deep underground to be securely and permanently stored away from the atmosphere in rock.[2]
Bellona Foundation	CO_2 emissions can be reduced significantly if CO_2 Capture and Storage (CCS) is implemented globally. CCS is the process where CO_2 is cleaned from large point sources, followed by transport of the CO_2 to a safe underground storage location where CO_2 is injected for long-term safe storage.[3]
Department of Energy and Climate Change, UK	CCS technology captures carbon dioxide from fossil fuel power stations. The CO_2 is then transported via pipelines and stored safely offshore in deep underground structures such as depleted oil and gas reservoirs, and deep saline aquifers. Up to 90% of carbon dioxide (CO_2) from a fossil fuel power station can be captured using CCS technology.[4]
U.S. DOE	CCS encompasses the entire life-cycle process for controlling CO_2 emissions from large-scale point sources such as coal-based power

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[1] http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter1.pdf

[2] http://www.globalccsinstitute.com/ccs/what-is-ccs

[3] http://www.bellona.org/articles/articles_2007/CCS_facs

[4] http://www.decc.gov.uk/en/content/cms/emissions/ccs/what_is/what_is.aspx

	plants. By cost-effectively capturing CO_2 before it is emitted to the atmosphere and then permanently storing it, coal can continue to be used without restricting economic growth while still reducing carbon emissions to the atmosphere.[5]

CCS is also important to reduce China's carbon emissions, while at the same time satisfying its increasing demand for electricity and chemical products and its continual reliance on coal. As China's major province of energy and natural resources, Shaanxi Province has abundant coal resources and is listed as one of China's low carbon demonstration provinces. However, as a western and underdeveloped province, its energy structure is dominated by coal and the heavy chemical industry is still an important pillar industry in promoting economic growth. During the 'Eleventh Five-Year' (during 2011-2015) period, Shaanxi Province exceeded the task of energy saving, but high energy-consuming industries such as power, chemical, petrochemical, nonferrous metal, metallurgy and building materials contributed to more than half of Shaanxi's output value. The conflict of resource usage and environmental protection has become increasingly prominent, and this economic pattern is difficult to fundamentally change in the short term.

CO_2 emissions of Shaanxi Province mainly derive from the consumption of fossil fuels. In 2005, they were 138 million tons and accounted for 2.4% of China's total emissions. Thermal power plants are the main source of CO_2 emissions in Shaanxi Province, accounting for about 70% of the total; this is followed by the cement industry, accounting for about 10%. In addition, ethylene and synthesis ammonia industries account for about 10% and hydrogen production industry accounts for around 0.7%. According to preliminary measurements and estimates, CO_2 emissions from fossil fuels in Shaanxi Province had risen from 138 million tons in 2005 to 209 million tons in 2009, and before 2015 it may reach 450 million tons. In the coal chemical industry, CO_2 emissions are expected to reach 180 million tons by 2015. This is due to the high energy-consumption in this industry, the associated large CO_2 emissions and the constant development of large-scale coal chemical projects for the future.

The implementation of early CCUS demonstrations in Shaanxi Province is of great significance. Firstly, Shaanxi Province urgently needs low carbon technology and CCUS is good for encouraging and developing this. Secondly, the chemical industry in Shaanxi Province is developed and has high-purity CO_2 sources. This can reduce the implementation cost of CCUS in Shaanxi Province and is good for promoting the entire CCUS demonstration. Moreover, the Shaanxi provincial government holds a positive attitude to a CCUS project. Implementing early CCUS demonstrations in Shaanxi Province can help to build the image of Shaanxi as a clean energy province.

1.2. Matching non-power industrial high purity CO_2 sources to EOR and other utilisation

Preliminary work on CCS in China has focused on the power sector. However, capture in the power sector is technically challenging, energy-intensive and expensive. Capture can be achieved at lower cost at large point sources of concentrated CO_2, such as in fertiliser plants, coal-to-liquids facilities

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[5] http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CCSRoadmap.pdf

and refineries. China has a large industrial base in these sectors, resulting in a significant CO_2 emission reduction potential through CCS.

In recent years China has seen the development of Enhanced Oil Recovery (EOR) activities. EOR injects CO_2 in oil reservoirs to enhance production and prolong the life of the reservoir. EOR is widely applied in the United States and Canada and is in development in the Middle East. China has a large EOR potential and an EOR industry is emerging. CO_2 from nearby high-concentration point sources has a value for EOR operations. This value can be used to develop early cost-effective CCS projects involving industries where capture cost are relatively low.

To date, a number of separate preliminary pilots for the capture and storage of CO_2 have been, and are being, undertaken in China. However, none of these pilots succeed in cost-effectively establishing a fully integrated CCS chain, due to insufficient coordination between capture and storage sectors.

Early demonstration of cost-effective CCS potential in selected sectors can significantly advance CCS development in selected industries in China, in time crossing over into other sectors including power, as the technology and policy conditions mature.

Carbon capture potential and the cost in these industries have been explored by directly engaging stakeholders from the relevant industries and the EOR sector. This helps to inform the National Development Reform Commission (NDRC) and the Ministry of Science and Technology (MOST) in identifying and better coordinating potential CCS early stage demonstration projects, while building awareness in these industries about potential opportunities for collaboration in CCS.

1.3. Availability of information

The main task of this project is to support early CCS opportunities in the non-power sector. First of all, the CO_2 emission sources in non-power sectors should be identified; then the potential CO_2 sinks and their geological conditions should be confirmed; lastly, potential CCS projects should be suggested and evaluations made. However, as for the emissions sources, the information of the plant type, scale, enterprises' names and so on are always available online. As for the sinks, some information can be obtained from the oil companies' homepages and existing publications. We have taken part in a lot of CCS activities in China and have good cooperation with some oil fields, therefore we can learn something from the outputs of the past projects or we can inquire directly from the oil fields. Also, according to our preliminary investigation, some oil fields such as the Yanchang oil field in Shaanxi Province, have showed great interest in CO2-EOR projects, so the information about this project can become available.

Altogether, we can gather information in different ways. Firstly, by searching online – for example, through the homepages of some giant enterprises, such as Yanchang Oilfield, we learned the basic situation of the industry; through online yellow pages, we gained more detailed information about the company yield, location, etc. of Shaanxi's chemical, power, construction industries related to CCS projects. Secondly, we held some workshops with experts in the relevant fields. This proved instrumental in fulfilling this report. In addition, we conducted a questionnaire surveys for CO_2 sources, sink industries and other relevant stakeholders.

2. Technical gaps and barriers

There are a number of specific technical gaps and barriers that exist to CCUS development that would need to be addressed in order to make deployment a reality. This section summarises the gaps and barriers that have been identified for each element of the CCUS chain: CO_2 capture and compression; CO_2 transport; and CO_2 utilisation in EOR or ECBM. Improving the understanding and performance of each element in the CCUS chain is critical to its effective demonstration and large-scale deployment. Technical gaps and barriers that are specific to China and Shaanxi province are also addressed.

2.1. Capture and compression

Unlike capture from the electrical power generation industries, CO_2 captured from high purity industrial sources may require little, if any, further treatment. The main requirement would be to compress the CO_2 to high pressures, usually over 100 bar, making it ready for transport and utilisation [1]. However, actual purity requirements of the CO_2 will depend on the application, transportation method and distance. Low oxygen concentrations are a strict requirement for use of CO_2 in EOR because it would react with hydrocarbons within the oil fields [2]. For long transportation distances, dehydration of the CO_2 stream is required in order to prevent corrosion and leakage of pipelines. However, moisture does not cause problems for EOR injection so appropriate metallurgy could be installed for pipelines such as stainless steel and this may be more economical for short transportation distances. CO_2 impurities may impact on compression or result in risk of phase change during transport; this may be a difficult problem to overcome for transportation networks with multiple CO_2 sources. Awareness amongst CO_2 source industries about the implications of impurities on transport and application in EOR is required and could be achieved by drafting recommended guidelines and standards. This would indicate to the source industries what steps are required to meet the necessary standards [3].

Capital and operating cost penalties of CO_2 compression are considerable for any CCS system. The CO_2 compressor power required for a coal to hydrogen plant is approximately 8% of the total plant energy requirement. For such plants the cost of CO_2 compression can lead to a 15% increase in the H_2 cost [4]. Techno-economic studies can help to estimate costs of required CO_2 capture, additional gas purification and compression of CO_2 derived from high-purity CO_2 sources and to assess the economic viability of projects in comparison of these expenses to emission taxes and revenue generated from sale of CO_2.

In comparison to other sections of the CCS chain, CO_2 compression uses relatively matured technologies with a high readiness level. Nevertheless, R&D efforts are being undertaken in a bid to reduce capital costs, increase efficiency, improve heat recovery and optimise the integration of compressors in the carbon capture process [5]. Addressing these areas will alleviate economic risk of CCS projects. To achieve these objectives, key gaps in understanding of the impacts of impurities in the CO_2 stream as well as the effects of different operating pressures, temperatures and flow rates must be addressed. Improved knowledge of the thermodynamic characteristics of CO_2 mixtures with impurities under conditions at or near to supercritical could be obtained by activity coefficient measurement and will benefit these aims. The impact of impurities in the CO_2 stream on corrosion of solid materials used for compression is another key area of research. Research is needed in order to compare and evaluate options and configurations for compression and liquefaction. Heat exchange data should be quantified for plant applications, including supercritical CO_2, and waste heat could be utilised to improve cycle efficiency. Compressors at the large scale required for CCUS applications are available but are a non-standard product and may need to be sourced internationally for Shaanxi Province. The speed at which CO_2 compression systems can adapt to changes in throughput are currently highly uncertain but demonstration projects will help to fill this gap in knowledge [6].

2.2. Transport

CO_2 is mainly transported in pipelines from source to storage site in the gaseous or liquid phase, as this is the most cost effective method for CCS [7][8]. Pipeline transport also has an advantage over other transport methods in that temporary storage requirements during transmission are bypassed because a steady stream of CO_2 can be delivered. Like CO_2 compression, transportation of CO_2 is a relatively mature technology in comparison to other parts of the CCS chain, with several projects having been employed in North America with application to EOR for a number of decades [1]. Nevertheless, research is being conducted to develop optimal CO_2 pipeline networks and to investigate the scale-up required for large-scale CCS deployment. Significant gaps in knowledge exist on the economics of CO_2 pipeline transport since most CCS techno-economic studies neglect CO_2 transportation costs or assume a given cost per ton of CO_2 transported. CO_2 transport requires an improved understanding of the thermodynamic characteristics of CO_2 at supercritical conditions, especially when anticipated impurities are present, which would also address research needs for CO_2 compression [6].

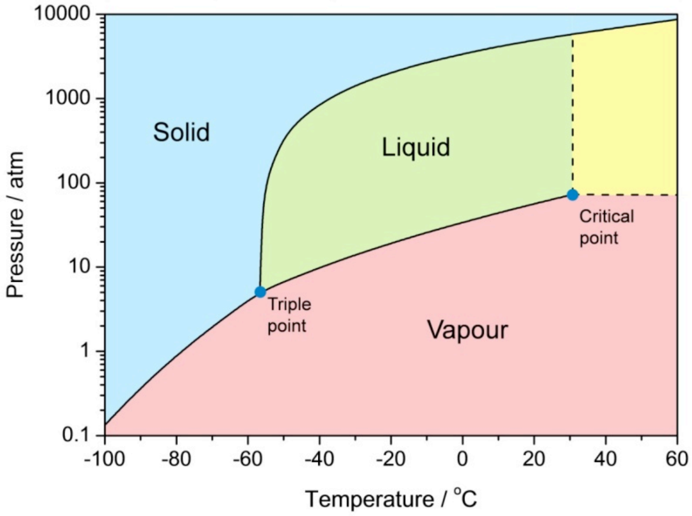

Figure 2.1. Phase diagram for pure CO_2.

Figure 2.1 shows the phase diagram for pure CO_2, which identifies its phase (solid, liquid or gas) for any given operating pressure and temperature. Two distinct features are shown on the phase diagram, namely: the triple point (5.1 atm, -56°C) and the critical point (73 atm, 31°C). In the vicinity of the triple point, CO_2 can exist as any one of the three phases. At temperatures and pressures above the critical point, CO_2 does not exist as a distinct liquid or gas phase but as a supercritical fluid, with the density of liquid but the viscosity of a gas. The most efficient state of CO_2 for pipeline is in the supercritical or dense phases in the vicinity of the triple point, which corresponds to a lower pressure drop along the pipeline per unit mass of CO_2 when compared to the transportation of the CO_2 as a gas or as a two-phase combination of both liquid and gas [9].

Today, over 2500 km of onshore CO_2 pipeline infrastructure is in operation in North America with a capacity of over 60 million tons of CO_2 per year. Elsewhere, a 90km onshore CO_2 pipeline is operated in Turkey for EOR and offshore pipelines in the North Sea are operated by Norway for CO_2 storage. In China, long distance CO_2 pipelines are not in operation but research is being carried out at Liaohe Oil field, where EOR is undertaken in order to investigate the impact of CO_2 release from a rupture in a 500m pipeline [10]. The requirements for construction of CO_2 pipelines are the same as those for hydrocarbon transportation so there is a strong understanding of the engineering principles. These pipelines can cover a wide range of environments, both onshore and offshore. However, there is still a significant lack of experience with regards to CO_2 transmission, especially with multisource transport and safety characteristics required for pipelines close to densely populated areas.

Variations along CO_2 pipelines such as flows, surges and the actual CO_2 composition must be accommodated by the system. Compared to extremely pure transported CO_2, streams from high-purity CO_2 sources are likely to have impurities which will impart changes to the physicochemical properties of the CO_2 stream and can increase the level of engineering complexity of the problem – very few engineers have the skills and experience necessary to make informed decisions on the safe design and operation of CO_2 pipelines. Therefore, key technical issues for CO_2 transport are the chemical, physical and transport properties with impurities in the stream. Consideration of pressures required to maintain CO_2 in the appropriate phase is needed whilst not exceeding safety limits at other parts of the system. Intermittency of CO_2 supply is a strong possibility with high-purity industrial sources, requiring careful consideration of the flow management in order to mitigate the occurrence of CO_2 phase change within the pipeline [11].

Guidance on procedures for the management of flow intermittency in CO_2 pipelines is extremely limited. Water in the system is undesirable, since it can react with CO_2 to form carbonic acid, which can corrode the carbon steel internal surfaces [12]. Sudden temperature drops with water present in the CO_2 stream could enable the formation of hydrates and clathrates, which are solid compounds with similar properties to ice; consequently they can lead to pipeline scaling and blockages in equipment, such as heat exchangers. The freezing of water is also an unwanted possibility [13]. For these reasons, the CO_2 stream should be dehydrated to levels below 50ppm of water prior to transport. Hydrate formation requires investigation to avoid operational downtime. Further investigations on the effects of other impurities on water solubility in supercritical CO_2 are merited. Hydrogen sulphide H_2S impurities should also be minimised due to the risk of internal pipeline carbon steel corrosion. Furthermore, impurities could potentially have an impact on non-metal materials used in pipelines, such as elastomers and polymers of seals and gaskets, so research is needed to investigate these effects. Efforts should be made to identify, quantify and document the impurities from high-purity CO_2 sources that will potentially remain within the stream through to storage or utilisation. An improved knowledge of internal corrosion rates of carbon steel and others in the presence of various impurities is very important for pipeline design and cost analysis; this could be obtained by investigating the level of corrosion in some of the oldest CO_2 and by performing experimental analysis on corrosion rates on new materials and pipelines at differing levels of moisture in order to evaluate the risk of accidental intake of humidity [6].

Some CO_2 purification may be necessary for the requirements of pipeline transport. High levels of CO_2 will enhance capture rates. There are currently no industry standard composition requirements imposed for CO_2 transportation. CO_2 composition requirements are set in contracts between the supplier and transporter and between the transporter and storage operator [14], and are often dependent on the end use (storage or EOR). For the purpose of CO_2-EOR, purity of over 95vol% is required. At this level, and under reservoir pressure [15], miscible conditions can be achieved whereby the CO_2 can mix in all proportions with the components in the oil, leading to the annulment of interfacial tension. For miscible EOR, high purity CO_2 should be compressed and cooled so that it is in the supercritical phase. The presence of non-condensable impurities such N_2 or Ar can impact the phase behaviour of the mixture and may make achieving a supercritical fluid impractical. Therefore, the design and operation of CO_2 pipelines requires careful consideration of impurity levels due to their effect on the supercritical phase behaviour. Networks of CO_2 pipelines could raise challenges not yet experienced as two-phase flow may occur in CO_2 pipelines where a supercritical regime is desired when impurity levels vary from source to source and this may also lead to significantly higher pressure drops. A standard set of entry specifications for CO_2 pressures, temperatures and impurities concentration would be required where multiple CO_2 sources connect to the same pipeline network, which may be prescribed by the EOR or storage operator and have a large bearing on upstream dehydration, compression technologies [11].

Further research, development and demonstration is needed to obtain improved thermodynamic models of CO_2 or mixtures of CO_2 with impurities such as argon (Ar), nitrogen ($N_2^{)}$, oxygen (O_2) carbon monoxide (CO), ammonia (NH_3) and hydrogen sulphide (H_2S) under supercritical conditions and near to the critical conditions as current equation of state models inadequately predict the phase behaviour. Improvements to these models could allow investigations into less energy intensive or more economical methods of producing supercritical CO_2 and could also address optimal solutions to the integration of compression and transportation systems [6].

Mapping of potential CO_2 source and sink matches in China [16] and Shaanxi [17] show that implementing CCUS may require long-range transportation by pipelines. As CO_2 transport is a relatively mature technology, this should not represent a major technical hurdle as the operating CO_2 pipelines in North America have demonstrated. No injuries or fatalities have occurred with CO_2 pipelines but 10 failure incidents were reported between 1990-2001 and it is reasonable to conclude that the level of safety is comparable to natural gas pipelines [18]. Despite the pipeline engineering experience and maturity of technology in North America, existing engineering and regulatory guidelines and experience worldwide are limited and a number of additional engineering gaps and challenges have been identified. Fracture propagation in CO_2 pipelines is a credible problem and the level of resistance required needs to be defined for various levels of impurities. Improved models for pipeline fracture propagation are required and these should be validated against full-scale crack arrest testing. CO_2 pipeline blowdown and depressurisation may occur as a result of an intentional controlled evacuation of pressurised gas or as a result of some incident such as valve malfunction, operational error or external damage. There are currently no validated models available for unplanned blowdown involving rapid decompression and temperature drop [19]. Supercritical/dense phase CO_2 release data is also required to verify any developed models. This information will help to define adequate safety zones around CO_2 pipelines.

Significant costs can be incurred in both further gas-clean up and by the problems associated with CO_2 pipeline impurities. Further studies are required to evaluate the economic trade-offs between gas-clean up, keeping impurities in the CO_2 pipeline and upgrading pipeline materials. Improved thermodynamic models for supercritical CO_2 mixed with impurities needed for simulation of hydraulic flow would also help to achieve this goal. As the number of CCS projects increases in a region it may be more economical to operate pipeline network. This raises a question if early opportunities for CCUS should invest in high capacity pipelines which other future projects could connect to or whether building individual pipelines would be cheaper as they may circumvent costs associated to CO_2 entry condition requirements (i.e. temperature, pressure and contaminant levels). Studies, which include hydrodynamic modelling for CO_2 pipeline design in China, have begun to emerge [20].

2.3. Storage: EOR and ECBM

EOR techniques are employed to increase the amount of crude oil that can be extracted from an oil field. The techniques can increase reservoir pressure and improve oil displacement or fluid flow in the reservoir. There are three main types of EOR, namely: chemical flooding, thermal recovery and gas injection. Gas injection uses N_2, hydrocarbons or CO_2 (CO_2-EOR), which after injection into the reservoir either expand to push the oil towards the production wells (immiscible displacement) or dissolve within the oil, which decreases its viscosity and increases its flow (miscible displacement). Miscible CO_2-EOR is one of the most promising of the developed technologies because when CO_2 mixes with the oil it forms a low viscosity, low surface tension fluid which is more easily displaced. In addition, CO_2 can release and reduce trapped oil as well as occupying reservoir zones that water cannot [21].

CO_2-EOR has been operating successfully in the US for over 30 years, with most miscible displacement projects being located in the Permian Basin fields of western Texas and eastern New Mexico. Every day, approximately 30 million m^3 of CO_2 is delivered by pipeline to the Permian Basin and around 30 million tons of CO_2 has already been sequestered there. The increasing number of CO_2-EOR projects worldwide has generated significant experience and has provided valuable insights into the underlying physical and chemical mechanisms for oil recovery [22].

In China, the first large scale CO_2-EOR and storage project is being conducted by PetroChina at Jilin Oilfield, located in Jilin Province of Northeast China. The CO_2 source comes from nearby natural gas production where it is stripped and condensed before being injected via six CO_2 injectors at the oilfield complex. So far, nearly 150,000 tons of CO_2 has been injected for miscible flooding with an expected 10% enhancement to recovery [23]. Given that many low permeability oilfields have been found in China in recent years and these are quite suitable for CO_2-EOR, the storage potential could be vast [24].

CO_2-EOR was not intrinsically developed for climate change mitigation and its goals are somewhat different to the geological sequestration of CO_2; in CO_2-EOR the aim is to maximise oil-production and to reduce costs by minimising the amount of CO_2, whereas for geological sequestration the aim is to maximise the amount of CO_2 stored [25]. However, CO_2-EOR does amount to geological storage in practice because very little CO_2 gets returned to the atmosphere. Significant volumes of

CO_2 can be recovered from production wells and then be re-injected; EOR operators seek to recycle as much CO_2 as possible in this way due to its cost of production. The amount of non-recycled CO_2 has been estimated by EOR operators to be anywhere between almost negligible to around 5% [26].

More than half of the current CO_2-EOR projects use CO_2, which is supplied from natural sources and does not contribute to any climate change mitigation. Nevertheless, there are a number of projects in North America, which use approximately 10 million metric tons per year of CO_2 from anthropogenic sources in total [27]. Anthropogenic CO_2 comes from a variety of sources such as natural gas processing and coal gasification for production of ammonia involving water gas shift reaction to convert carbon monoxide CO to CO_2. These industrial CO_2 sources are usually easy to utilise for EOR, requiring little or no additional purification. The costs of CO_2 from naturally occurring sources are roughly 25 to 50% of the cost of the capture costs from coal-fired power stations. However, the cost of CO_2 from high purity industrial sources is about the same as that of naturally occurring sources because the separation of CO_2 is already an inherent part of the process [6].

Despite the large amount of experience of sequestration of CO_2 via EOR, there are still a number of gaps and barriers that could hinder its widespread deployment for CCS. For example, the distance between CO_2 sources and oil fields could be large and nearest oil fields might be unsuitable for CO_2-EOR or the storage capacity could be insufficient. In all cases, full seismic analysis is required and the storage media should be well characterised in terms of petrology, mineralogy and rock/rock-fluid properties [28]. Some key issues for CO_2-EOR are listed here:

- Reasonably simple expressions can be used for estimating the CO_2 storage potential in a CO_2-EOR project. The methods are based on the assumption that the theoretical CO_2 storage capacity in oil reservoirs is equal to the volume previously occupied by the produced oil and water [29]. However, the main drawback to these methods is the lack of data and their uncertainty due to the lack of consideration of important engineering or economic factors; hence they are not reliable. More accurate predictions of CO_2 storage capacity can be obtained by using numerical reservoir simulations, which may take into account the effect of water invasion, gravity segregation, reservoir heterogeneity and CO_2 dissolution in formation water [30]. Basin or country specific estimates may be more accurate but are limited by the availability of data and the methodology used; such estimates may not be available for certain regions.

- CO_2 trapping mechanisms (i.e. volumetric, solubility, adsorption and mineral trapping) that determine the long-term fate of CO_2 require a better understanding [6].

- Risks associated with leakage of CO_2 injected as part of an EOR project should be quantified and regulated for public safety and assurance. The possibility of CO_2 leakage might follow two pathways. The first and most probable is that CO_2 migrates out of a well, either the project well or a nearby well that is improperly sealed; the second unintended way of leakage is via unidentified faults or fractures [31]. Unintended leakage of CO_2 from underground to the surface could result in the asphyxiation of humans and animals, have an impact on plants or ecosystems and may also contaminate drinking water sources [32]. Field data should be collected on permanence of storage and high-level computer simulation could also aid the analysis of leakage risks. Furthermore, information from the natural gas storage and the natural CO_2 production industry could be used to provide analogies and lessons for CO_2 [6].

- The possibility of CO_2 injection causing induced earthquakes is believed to be remote but site specific assessments should be carried out [26].

- Understanding the impact of impurities is an area that requires further research. High-purity CO_2 sources arising from coal gasification often contain levels of H_2S. In the presence of SO_2, deposition of elemental sulphur could occur, which could lead to severe pore blocking [33]. Although H_2S is an efficient solvent that miscibly displaces oil, the acids it forms by contact with brine could make production handling expensive [34]. The effect of impurities on the minimum miscibility pressure also requires further understanding.

- Rather than considering the maximum CO_2 storage capacity, traditional approaches for CO_2-EOR tend to optimise oil production efficiency by limiting the amount of CO_2 used for injection. Even this activity is considered as a 'black box' with several unknowns including proper material balance of the injected CO_2; how much will be dissolved in the water; how much will actually mix with the crude etc. [28]. Well simulation techniques for CO_2-EOR can help to fill this gap. Further information and experience is also required on maximising storage capacity in conjunction with CO_2-EOR – this will involve redesigning CO_2-EOR projects and approaches [35].

- A final challenge relates to reservoir monitoring and management. A comprehensive reservoir monitoring and surveillance system is required to verify the storage integrity in reservoirs. This can be established by measuring pressure and changes to fluid chemistry in the reservoir, imaging seismic properties or recording microseismic activity in the reservoir and by sampling surface soil to test for traces of leaked CO_2. Management of the CO_2 flood pattern can be compounded by the lack of real time performance information.

Despite these gaps in knowledge that require filling in order to improve CO_2-EOR, it is believed that there are no major technical obstacles to this technology, since large-scale operations involving industrial CO_2 sources have already been proven in North America.

Enhanced Coal Bed Methane (ECBM) is a way of recovering methane from un-mineable coal seams and is considered to be a less mature technology than EOR. During the coalification process in coal seams, gases including CO_2 and methane CH_4 are produced. The gases are stored in the coal cleats and adsorbed onto the internal surface of the coal; this is distinct from conventional natural gas fields where it exists as a free gas in porous rock formations. Coal bed methane has often been recovered by reducing the overall pressure in the reservoir, either by pumping out or mining out water and then degassing the reservoir. Injection of inert gas – either N_2, CO_2 or a combination of the two – is another method of recovery, which has the advantage of higher yields. Injection of N_2 into the reservoir promotes methane desorption by lowering the partial pressure of methane in the reservoir without lowering the total reservoir pressure. CO_2 has a higher adsorptivity on coal than methane and will therefore displace it – this also leads to an effective mechanism for CO_2 sequestration.

There are currently no large-scale field operations of ECBM with gas injection. However, there are a number of pilot-scale demonstration projects across the world. The earliest of these have been conducted at the San Juan Basin in the south western United States by Amoco using N_2 or CO_2 as the injected gas. In Alberta, Canada, field tests have been carried out using CO_2 or CO_2/N_2 mixtures [36]. The RECOPOL CO_2 sequestration and ECBM demonstration project in Poland is the first of its kind in Europe and outside of North America and injects CO_2 into the Silesian Coal Basin. The Ishikari Coal Field in Japan has hosted another pilot CO_2-ECBM project [37].

In China, a pilot scale ECBM project is taking place at the Qinshui Basin in Shanxi Province. The Qinshui Basin is one of China's foremost primary coal bed methane (CBM) producing regions. It is operated China United Coal Bed Methane Corp. Ltd. (CUCBM) who have the exclusive rights for exploration development and production of CBM in cooperation with foreign companies. The Qinshui Basin was selected due to its large area, thick continuous coal seam, high gas contents and shallow depths of coal seams. It also has reasonable access to pipelines and has been explored relatively more than other basins [38]. Preliminary results of the project have been promising and it has been shown that the amount of methane that can be produced compared to primary CBM was substantially enhanced and that CO_2 storage in the high rank anthracite coal is feasible [39]. The Chinese ECBM recovery potential has been estimated to be over 3.7 trillion m^3 and the sequestration potential is about 142.67 Gt [40].

As with CO_2-EOR, CO_2-ECBM requires a relatively pure stream of CO_2 for injection, although high levels of N_2 can be accommodated. There are no natural sources of CO_2 in or near the Ordos coal basin in China [41], meaning that appropriate matching with a high purity industrial source or a source from the power generation industry would be crucial for the success of these projects.

As CO_2-ECBM is a relatively new concept, the technical gaps and barriers are considered to be more of an obstacle in comparison to CO_2-EOR and they need to be overcome by vigorous programmes of fundamental and applied R&D. Before widespread deployment can occur, a key technical issue of the reduction in coal permeability after CO_2 injection due to coal swelling must be resolved. In order to enable reservoir modelling and simulation, the effects of CO_2 injection rate, total gas pressure, formation temperature and gas composition on coal swelling/shrinkage and adsoption/desorption of gases on coal surfaces must be adequately quantified. Some of the main challenges for CO_2-ECBM are listed here:

- The interplay between the physical mechanisms of multicomponent diffusion and adsorption requires a better understanding for effective simulation [42].
- Models for response of the coal pore structure to gas injection and the impact this has on the coal swelling or shrinkage require further development.
- The impact of coal matrix-fracture interactions on the time-dependent coal permeability is still unclear [43].
- The integrity of CBM CO_2 geological storage systems and reliable monitoring of these are critical issues, which require further work in order to gain public acceptance.
- A problem arises in regards to what exactly constitutes an unmineable coal seam because what is considered umineable with current levels of technology, expertise and coal price might change to economically viable in the future. A future risk is posed for currently legitimate coal seam sequestration sites of future CO_2 release or obstructing the utilisation of the coal as an energy resource. Criteria for establishing location specific definition of unmineable coal are required.
- Final challenges for CO_2-ECBM are the lack of information on the available storage capacity in unmineable coal seams and the lack of geological and reservoir data required for defining good settings for CO_2 injection and storage [44].

Despite these challenges, there is continued interest in CO_2-ECBM because of the large coal deposits across the world, economic value of ECBM potential and the existing CBM infrastructure, which could be used for enabling CO_2 storage projects [44].

2.4. Impact of CO_2 impurities

This section summarises the impacts of impurities in the CO_2 stream across the CCUS chain from compression through to transport and storage and outlines research gaps. Guidelines for impurity levels as provided by other authors are given. Little data is available on recommended impurity levels for CO_2-ECBM due to the immaturity of the technology but some discussion is given below.

A large majority of previous studies have focussed on the impacts of impurities on pipeline transportation. The DYNAMIS European project [45] made recommendations on allowable impurity levels for transport via pipelines for pre-combustion and post-combustion processes. The impacts of the impurities on application of the CO_2 for EOR were also discussed. There are parallels that can be drawn from CO_2 sources derived from pre-combustion carbon capture power generation and high purity industrial sources of CO_2 derived from gasification, such as, coal-to-liquids (Fischer-Tropcsh) or ammonia/fertiliser plants. The concentration limits and an explanation of the technical or safety limitations are given in Table 2.1.

Table 2.1. DYNAMIS recommendations for CO_2 quality [45,33]

Component	Concentration	Limitation
H_2O	500 ppm	Technical: below solubility limit of H_2O in CO_2. No significant cross effect of H_2O and H_2S. Cross effect of H_2O and CH_4 is significant but within limits for water solubility
H_2S	200 ppm	Health and safety considerations
CO	2000 ppm	Health and safety considerations
O_2	Aquifer < 4 vol%, EOR < 100 – 1000 ppm	Technical: range for EOR because of lack of practical experiments on effects of O_2 underground
CH_4	Aquifer < 4 vol%, EOR < 2 vol%	Energy consumption for compression and miscibility pressure for EOR
N_2	< 4 vol % (all non-condensable gases)	Energy consumption for compression
Ar	< 4 vol % (all non-condensable gases)	Energy consumption for compression
H_2	< 4 vol % (all non-condensable gases)	Further reduction of H_2 is recommended because of its energy content
SO_X	100 ppm	Health and safety

		considerations
NO_X	100 ppm	Health and safety considerations
CO_2	>95.5%	Balanced with other compounds in CO_2

Impurities in the CO_2 stream may cause changes to the physical properties of CO_2 in comparison to pure CO_2 that may have implications for geo-sequestration. Geological storage capacity could potentially be reduced by impurities by the replacement of CO_2 and also by reducing the CO_2 stream density since they are not as easily compressed as CO_2. The decrease in density experienced by the presence of less compressible impurities can also affect injectivity because it will decrease the mass flow for the same pressure drop; however, the addition of impurities will also lead to a decrease in viscosity, which would increase the mass flow. Both the density and the viscosity will be controlled by the temperature and pressure; however, there is a lack of experimental data required to validate viscosity calculations. The effect of impurities on injectivity is less than that of storage but could still be significant under certain circumstances. In addition, the decrease in density can also lead to an increase in buoyancy of the plume. The buoyancy of a CO_2 plume can be increased by 50% for a case of 15% impurities, which in turn could lead to a three-fold rising velocity increase; subject to reservoir conditions, this could potentially reduce residual trapping and increase the lateral spreading of the plume [33].

Impurities within the CO_2 stream can have chemical effects which impact on the reservoir, caprock and well cement. The species with the most significant effects are NO_X, SO_X and H_2S because these species can oxidise to form nitric acid or sulphuric acid, thus lowering pH [46]. These acids may affect long term caprock porosity and permeability due to the occurrence of dissolution of carbonates or sandstone [47]. The impurities can accelerate the corrosion of steel and cement well materials.

High levels of O_2 in CO_2 streams used for EOR are known to cause overheating at the injection point, oxidation in the reservoir leading to higher oil viscosity with increased extraction cost and increased microbial growth with unknown effects on oil production [48]. High levels of O_2 are a main concern with streams derived from oxyfuel combustion carbon capture but may not be expected in CO_2 streams derived from gasification. The impacts of the impurities of SO_X and NO_X relating to experience to date with EOR have been discussed by Bryant and Lake [49] with the conclusion that the impurities are unlikely to adversely affect the recovery and have an insignificant effect on injectivity.

CO_2 impurities have a different effect on the storage capacity of CO_2-ECBM applications. H_2S and SO_2 have a higher affinity to coal compared to CO_2 and so will preferentially adsorb on to the coal surface thus reducing the CO_2 storage capacity [50]. O_2 impurities will react irreversibly with the coal surface and therefore reduce the surface for sorption and storage capacity.

Some gaps and recommendations relating to CO_2 impurities are summarised here:

- Accurate equations of state are required for CO_2 mixtures containing impurities in order to improve modelling predictions for compression, transport and storage. Experimental data is needed in order to calibrate parameter values and to vialidate model predictions.

- The viscosity of the CO_2 stream affects pipeline transport, injectivity and migration of the CO_2 stream in storage. There is a lack of experimental data on the effect of impurities on the CO_2 viscosity, which is required to construct and verify numerical models.
- Long-term testing is needed for materials exposed to CO_2 containing impurities at all stages of the CCUS chain and predictive models for corrosion rates prediction should be improved.
- The impact of CO_2 impurities on sub-surface chemistry and prospects for long-term safe storage requires an improved understanding.

3. Economic Gaps and Barriers

3.1. Existing CCUS infrastructure

With the increasing focus on CCUS in China, some infrastructures have been built. The existing/planed infrastructures are listed in Table 3.1.

Table 3.1: Existing and planned CCUS infrastructures in China.

Project	**Capture Method**	**Storage/Usage**	**Scale**	**Current Situation**
Beijing Thermal Power Plant Capture Project, Huaneng Group	Post-combustion Capture	Food industry, industry	3,000 tons/year	Under operation
Shanghai Shidongkou Power Plant Capture Project, Huaneng Group	Post-combustion Capture	Food industry, industry	120,000 tons/year	Under operation
Chongqing Shuanghuai Power Plant Capture Demonstration, China Power Investment Corporation	Post-combustion Capture	N/A	10,000 tons/year	Under operation
Jilin Oil Field CO_2-EOR R&D project, China National Petroleum Corporation	Natural Gas CO_2 Separation	EOR	0.8-1 million tons/year	Phase I finished; Phase II ongoing
Biodegradable Plastic Production using CO_2, China National Offshore Oil Corporation	Natural Gas CO_2 Separation	Biodegradable Plastic Production	2,100 tons/year	Under operation
CO_2-ECBM Project, China CBM	Purchase	ECBM	40 tons/day	Suspended
New Chemical Material	CO_2	Chemical	8,000	Under

Production using CO_2, ZHONGKEJINLONG Chemical Co., Ltd	Captured From Alcohol Plants	Material Production	tons/year	operation
GreenGen Tianjin IGCC Demonstration, Huaneng Group	Pre-combustion Capture	EOR		Phase I ongoing
Lianyungang Clean Energy Demonstration	Pre-combustion Capture	Saline Aquifer Sequestration	1 million tons/year	Preparatory
Hubei Yingcheng 35MWt Oxy-fuel Combustion Demonstration	Oxy-fuel	Salt Mine Sequestration	100,000 tons/year	Preparatory
CCUS Demonstration, China Guodian Corporation	Post-combustion Capture	Food industry	20,000 tons/year	Preparatory
Microalgae Carbon Sequestration Bio-energy Demonstration, ENN Group	CO_2 Captured from Coal Chemical Industries	Bio-sequestration	320,000 tons/year	Ongoing
CCS Project, Shenhua Group	CO_2 Captured from Coal Liquefaction Industries	Saline Aquifer Sequestration	100,000 tons/year	Under Operation
Shengli Oil Field CO_2-EOR Demonstration, Sinopec Group	Post-combustion Capture	EOR	30,000 tons/year	Under Operation
CCS-EOR Demonstration			1 million tons/year	Preparatory

From Table 3.1, we can see that China has done a lot of works and has a leading place in CCUS field.

3.2. Age and lifespan of CO_2 sources and sinks

The lifespan of CO_2 sources are different for different types. Typically, for ordinary chemical or power plants, their lifespan is about 20–30 years.

For CO_2 sinks, their lifespan depends on the CO_2 storage capacity and the CO_2 injection rate. However, for a big oil field, the injection of CO_2 can last for several tens to more than one hundred years.

Thus, for a CCS demo, the math of the age and lifespan between the CO_2 sources and sinks is not a big problem.

3.3. Investment needs

According to the IEA research, in the background of controlling temperature rises by 2°C till 2050, as the technology of improving energy efficiency contributes less in CO_2 emission reduction and developing alternative energy is more and more difficult, the contribution proportion to CO_2 emission reduction by CCS will increase from 3% in 2020 to 10% in 2030, and reach 19% in 2050. IEA reports that 100 CCS projects and 130 billion dollars will be needed till 2020 around the world (21 projects and 19 billion dollars for China and India); 3,400 CCS projects and 5.07 trillion dollars will be need till 2050 around the world (190 projects and 1.17 trillion dollars for China and India).

When applying CCS technology in a power plant, cost input will increase by at least 50% and the final user cost will increase by 20% as well. For the three stages of CCS, capture costs the most (about 80% of the total cost) while transport and storage take about 10% respectively.

If CO_2 is captured in a chemical plant, for example the methanol plant, investment around 1400–1500$/kW is needed. Thus, for a plant with a scale of one million tons methanol, the total investment would be $85–90\times10^8$ US$.

As for the CO_2 pipeline with a diameter 1m, around 60,0000US$/km is needed to transport CO_2 high-pressure conditions.

Weyburn CO_2-EOR in Canada is an exsiting and successful project. The EOR is expected to enable an additional 130 million barrels of oil to be produced and extend the life of Weyburn Field by 25 years. Ultimately 20 million tons of CO_2 are expected to be stored. The current cost is $20/ton of CO_2. A 330km (205 miles) long pipeline transfers the CO_2 from Beulah, North Dakota, to the Weyburn field in Saskatchewan, Canada. There are two projects in tandem at the Weyburn Field: the commercial EOR project run by EnCana; and the research project looking at the potential to store CO_2, run by the PTRC. The research project was formally known as the International Energy Agency Greenhouse Gas Weyburn-Midale CO_2 Monitoring and Storage project. The eight-year project, which will increase oil production and CO_2-EOR research, is estimated to cost $80 million. In July 2010, the U.S. and Canadian governments jointly pledged an additional $5.2 million in new funding. The DOE has provided $3 million and the Canadian Government $2.2 million. The CO_2 injection is on two sites, Cenovus Energy owned Weyburn Field and Apache owned Midale Field. The EOR has increased production from Cenovus's Weyburn field by 16,000-28,000 barrels a day and by 2,300 to 5,800 barrels a day for Apache's Midale Field.

3.4. CO_2 taxation

CO_2 taxation is a price instrument that can be used to internalise the envisaged negative effects of CO_2 on society. The instrument works by requiring emitters to pay a fee per ton of CO_2 released to the atmosphere. Regardless of which sector of the economy is exposed to the instrument, the CO_2 tax increases the cost of operation, whether driving a car or running a coal-fired power plant. From an industrial or power generation perspective, emitters can either choose to the pay the tax or invest in CO_2 abatement technologies or energy efficiency measures. The choice will be made on a simple economic decision dependent on the price of the CO_2 tax and the cost of the abatement technologies available.

In order for CO_2 taxation to act as an incentive for CCUS, the tax must exceed the marginal abatement cost of a CCUS project. In Norway, a CO_2 tax of approximately US$50/t$CO_2$ has encouraged the oil and gas industry to invest in two large CCS projects, Snohvit and Sleipner, with a combined storage of almost 2MtCO_2 per year. These CCS projects involves collecting (rather than venting) the CO_2 that is stripped from natural gas processing plants, a relatively low cost form of CO_2 capture.

In China's Twelfth Five-Year plan, it was stated that government researchers have proposed a carbon price of RMB 9.5 ton CO_2 (US$1.5) in 2013 rising incrementally to between RMB 48 and RMB390 yuan/ton CO_2 (US$7.30 and US$59) in 2020. At the upper limits of this range, the CO_2 tax may certainly encourage the deployment of a CCUS project. The CO_2 tax will be applicable to any process that emits CO_2, and no differentiation between sectors is foreseen. It is proposed that the CO_2 tax will be introduced as a pilot scheme in 13 provinces starting in 2013, however Shaanxi Province is not named as one of the pilot provinces. The primary reason for the introduction of a CO_2 tax is to avoid frictions of trade with the US who, under the American Clean Energy Security Act established in 2009, has considered placing carbon tariffs on the import of goods from China.

4. Policy and Regulatory Barriers

4.1. Current CCUS policy

Policies related to CCUS in China are primarily concerned with supporting R&D of the technology and the development of demonstration projects, such as the 400MW GreenGen demonstration project in Tianjin, which is due to be completed over the next five years. R&D in CCUS has been initiated within a number of multi-annual programme plans including (51):

National Medium- and Long-Term Programme for Science and Technology Development (2006-2020), State Council, 2006 - *"To develop efficient, clean and near-zero emission fossil energy utilisation technologies"* – highlighted as an important frontier technology

China's National Climate Change programme (2007-2010), State Council, 2007 – CCUS technology was included as one of the key GHG mitigation technologies that shall be developed.

China's Scientific and Technological Actions on Climate Change (2007-2020), 14 Ministries including MOST, 2007 – CCUS technology was identified as one of the key tasks in the development of GHG control technologies in China.

The Ministry of Science and Technology, 2008 - *launched the National High Tech Program (863 Program) of Technology Research for CO_2 Capture and Storage.*

In addition, the Twelfth Five-Year guideline (2011-2015) released in March 2011, placed emphasis that CCUS will remain a priority R&D goal for the period. Also in the Twelfth Five-Year guideline, a number of structural market mechanisms are proposed to reduce energy intensity in industrial and energy sectors. According to The Climate Group (52), these market mechanisms include a resource tax reform, focused on an *ad valorem* tax on the energy resources used to make a product. Furthermore in October 2010, the 17th Central Committee of the Communist Party of China (CPC) approved proposals to establish an emission trading scheme on over the next five years, with targets being set in the five-year guideline as a 17% reduction in CO_2 emissions and 16% reduction in energy intensity compared to 2010 levels. However, it is unlikely, that the market-based mechanisms outlined above will be sufficient to incentivise CCUS deployment without public financial support in the near-term.

4.2. Integrating policy and legislation

In parallel to the development and commercialisation of CCUS technologies, a legislative or regulatory framework is a key enabling factor for the deployment of CCUS in any country. However, akin to the majority of countries across the globe, no legal framework exists in China that can regulate this multifaceted and innovative abatement technology. Basically, effective regulation is essential to ensure that CCS operations are conducted in a manner that causes no harm to people and the environment. In addition, regulation is also necessary to clarify issues of long-term liability, monitoring requirements and to guarantee remedial action in the case of CO_2 leakage or any form of damage caused through operations.

The link between policy and legislation is often unclear although very important. Commonly, policy is developed, and then the objectives of the policy are enforced, or encouraged, by the development of an enabling regulatory framework. To highlight the link between policy and legislation particularly in the field of CCUS, it is useful to look towards an example. Between 2005 and 2007, the first phase of the European Union's Emission Trading Scheme (EU ETS) was launched as one of the mechanisms to achieve the EU's climate policy goals. From 2013 (the start of third phase) CCS is fully recognised as an abatement option, meaning that CO_2 successfully stored is classed as 'not emitted', and the associated emission allowances under the EU ETS do not have to be surrendered.

However, CCUS projects attached to installations can only store CO_2 under the EU ETS if they comply with specific CCS regulation issued by the European Commission, the EU Directive on the geological storage of carbon dioxide[6]. The Directive, which should have been transposed into the EU's 27 Member States' national legislation by June 2011, sets out the legal requirements for CCS projects in terms of *inter alia* monitoring requirements, environmental impact assessments, site characterisation, liability and post-closure management. CCS projects may only take place in the European Union if they comply with the minimum requirements of the Directive as transposed in national legislation.

In addition to the EU CCS Directive mentioned above, an EU Decision was released in 2010, which outlines the guidelines for the monitoring and reporting of CO_2 emissions stored under the EU ETS[7]. These guidelines ensure that CO_2 captured, transported and stored under the EU ETS in accordance with the EU CCS Directive is monitored and reported in an appropriate and consistent

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[6] Directive 2009/31/EC

[7] Commission Decision 2010/345/EU

manner by all project developers. Therefore, the example above highlights the interaction between policy to encourage CCS, and the requirement for specific legislation to ensure that CCS projects are deployed in a safe and equitable manner.

4.3. Regulation of liabilities

Within a CCUS project, the actor liable for any damages caused from the capture, transport or storage components of the project may depend upon the ownership and operational organisation. The division of liability may also differ between the operational phase and the post-closure phase of the project. For issues of liability during the operational phase of the project, it is generally accepted by industry and authorities involved in CCUS that the operator, or the entity overlooking the activity, must assume liability for any damages occurred (53). If, for example, there are separate operators for the transport and storage components of the CCUS chain, it is assumed that these operators would assume liability and factor risk into any transport/storage tariffs charged to the emitter. An exception would be gross negligence by the capture operator, i.e. an impure CO_2 stream causing equipment malfunction. Whether liabilities could be attributed to third parties, i.e. equipment suppliers, given the cause of a leakage being faulty hardware depends on pre-existing contractual agreements.

For localised effects, for example surface leakage, impact of CO_2 on the subsurface, physical effects (e.g. induced seismic events) and occupational hazards, may fall under existing regulations such as administrative law (i.e. breach of authorisation conditions), criminal law (i.e. negligence) or civil law (damages to third parties) (53). Although CCUS as a technology is relatively new, from a legal perspective this is independent from the potential damages caused by the operations. Existing criminal law and civil law may be sufficient in China to allow for timely redress of any affected entities during the operational phase, and this is not understood to be a barrier given that existing mining and oil/gas extraction activities entail very similar liability risks as CO_2 storage. Nevertheless, regulations that stipulate the legal requirements for operating CCS projects must be developed if a court of law is to decide whether or not an operator was in breach of the authorised conditions for the project.

Long-term liability of CO_2 storage projects, once the operational phase has finished, is a challenging and complex issue. Private investors are unlikely to invest in a CCUS project whereby the period of liability for leakage is indefinite, particularly when the project is combined with a mechanism such as the EU ETS where the CO_2 stored could be worth millions of Euros in EU Allowances (carbon credits). Furthermore, if an accident were to occur 30 years after the operational phase had been completed, there is no guarantee that the firm responsible would be in a position to accept liability. In Europe, the EU Directive[8] states that after a minimum period of 20 years, the responsibility of the storage site may be passed onto the state government of the country where the project is taking place. In this case, if the operator can show that there is negligible risk of leakage at the site, the long-term liability (+20 years) will be accepted by the Member State. Dependent on the ownership structure, there may be CCUS projects that are owned or partially owned by the state government, and in this case there may be no transfer of liability issues (53).

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[8] Directive 2009/31/EC

4.4. Incentive provision to promote CCUS

Under certain circumstances the injection of CO_2 into oil fields for the purposes of enhanced oil recovery (EOR) can result in a business case for CCUS. In China EOR test injections with CO_2 have taken place in the Jilin Oil Field conducted by PetroChina, and results suggest that an additional 3.2 tons of oil can be recovered for every ton of CO_2 injected (51). The feasibility of EOR depends on the predicted responsiveness of the field, the cost of acquiring and transporting the CO_2, and the prevailing price of oil on global markets. In some cases, EOR is subsidised not for the purposes of CO_2 abatement, but for its contribution to national energy security. For example, in the US, to offset the costs of EOR the government provided tax incentives to companies engaged in the practise. The combination of EOR with crediting of the stored CO_2 emissions under a climate mechanism, such as the CDM, is a possibility, however there is an ongoing debate regarding how to account for the emission from the combustion of the incremental oil recovered through the process. Furthermore, the additional monitoring and reporting requirements for CCUS under the CDM will also increase the costs of the project.

Incentives for CCUS may also be created through the application of policy mechanisms, such as emissions cap-and-trade systems like the European Union Emissions Trading Scheme, a carbon tax, a baseline and credit scheme (such as the CDM) or an emissions standard. Unfortunately, given the high cost of CCUS, no market-based mechanisms have resulted in sufficient incentives to enable CCUS to this date.

Figure 4.1: Progression of incentive policy for CCS (54)

	Early stage	As technology matures	Late stage
1	Supporting capital deployment and operations	Greater willingness to invest by capital markets	Incentivising operations
2	Costs and risks shared by public and private sector	Reduced learning spill-overs and better knowledge of risks	Costs and risks mainly borne by private sector
3	Subsidising abatement	Polluter pays	Penalising emissions
4	CCS-specific support	Achieving least-cost abatement	Technology-agnostic policy

In a recent policy paper, the IEA [55] stated that in the early stages of CCUS deployment, incentives will be required in the form of CCUS specific financial support, with the technology subsidised by the public sector. Early CCUS projects can prove the viability of the technology and the information generated is of public interest. However, these pioneering activities entail excessive risk for the private sector to absorb individually. As the technology matures, and with the prospect of reduced costs through technological learning combined with increased private sector investment confidence, public support can be reduced. With potentially lower costs associated with CCUS, emission reduction policies can maintain incentives to invest in CCUS (or other abatement technologies) without the use of public funding.

4.5. Cooperation between multiple authorities

Given the multifaceted nature of CCUS the deployment of the technology will require involvement from multiple government institutions, national and local authorities, both from a policy and regulatory perspective. According to Liang et al (54), a large number of institutions in China at the national, provincial and municipal level share the responsibility for developing and implementing energy policies, and the authorization process for such projects has evolved rapidly over the last half century.

The World Resources Institute (56) has conducted a regulatory analysis for CCUS in China, and identified the relevant Ministries which would most likely be responsible for the development or modifications of regulatory acts. According to the World Resources Institute, the relevant environmental regulations for CCUS would be overseen by the Ministry of Environmental Protection (MEP), and the regulatory requirements for monitoring surface, water and sub-surface impacts would be the Ministry of Water Resources (MWR) and the Ministry of Land Resources (MLR). Although the national ministries outlined above would be responsible for the development of the national regulation, the provisional branches of the Ministries would be responsible for enforcing the regulation of individual demonstration projects (56). A non-exhaustive list of the legal acts relevant for CCUS and the responsible ministries in China is given in Table 4.1.

Table 4.1: Legal acts potentially relevant for CCUS and responsible ministries in China (56)

National Development and Reform Commission (NRDC) - Approving Domestic and Foreign Investment Projects
Ministry of Environmental Protection (MEP) - Water Pollution Control - Environmental Protection Law - Environmental Impact Assessment - Law and Standards on the Prevention and Control of Air Pollution - Solid Waste Pollution Law - Standard for Underground Storage of Hazardous Waste - Marine Environmental Protection
Ministry and Land and Resources (MLR) - Property Rights Law - Land Administration & Mineral Resources Law
State Administration of Work Safety (SAWS) - Protection of Oil and Natural Gas Pipelines - Provisions for Safe Supervision and Management of Petroleum and Natural Gas Pipelines
Ministry of Water Resources (MWR) - Water Law

Regarding the development of policy to support the deployment of CCUS in China, Liang et al have undertaken a study [54] to identify the perceived importance of various governmental departments in China in the authorisation and financing of large-scale CCUS demonstration plants. Through surveys and interviews with key stakeholders who have current or potential influence on the deployment of CCUS demonstration projects, including ministers from relevant departments, managers from energy companies and senior researchers from academic institutions, the importance and role of a range of government departments were identified (see Table 4.2).

Table 4.2: Chinese government departments and their potential roles in CCUS demonstration projects (table modified from 54)

Institution	Percentage of stakeholders naming institution as most important in authorising a CCS project	Perceptions of potential role(s) in authorising and financing a large-scale CCS demonstration power plant in China
National Development and Reform Commission (NDRC)	64%	Authorise the project at the national level. Provide financial and policy incentives. Issue guidance on technology options.
Local governments	9%	Provide fiscal and other forms of support. Authorise the project at the provincial and municipal level.
Ministry of Environment Protection (MOEP)	7%	Monitor and verify operations. Assess the environmental impact.
The State Council	6%	Influence the decision of NDRC and other ministries.
Ministry of Finance (MOF)	4%	Approve and audit the financial incentive needed for demonstrating CCS.
Ministry of Science and Technology (MOST)	3%	Provide scientific research grants to partially support CCS demonstration project.
State Electricity Regulatory Commission (SERC)	2%	Review and regulate the electricity tariff for CCS project approved by NDRC.

As can be seen in Table 4.1, from the stakeholder interviews, the National Development and Reform Commission (NDRC) is clearly perceived as the most important institution for enabling the development of CCUS demonstration projects. Although not included in the table, 33% of the interviewees mentioned local governments as the second most influential institutions. The alignment of national and local political support for CUCS is essential for the success of a demonstration project. A misalignment of national and local policies for CCUS is stated as one of the key reasons for the cancellation of a flagship CCS demonstration project in the Netherlands [56].

In order to improve the coordination between multiple authorities in the development of CCUS, certain countries have chosen to establish a so-called ‘interagency CCS Task Force’. One such Task Force was established by the Obama administration in the United States in 2010, is chaired by the US Department of Energy (US DOE) and the Environmental Protection Agency (EPA), and also involves nine different department and offices. Its is to develop a comprehensive and coordinated strategy to accelerate the development and deployment of clean coal technologies, with a key milestone of realising five to ten demonstration projects by 2016. A similar CCS Task Force was established in the Netherlands in 2008. This task force involved not only members of relevant government organisations, but also industry representatives and members of relevant non-government organisations, such as the Netherlands Foundation for Nature and Environment.

4.6. Harmonising policies in an international context

It may be possible for China to implement CO_2 abatement policies that could link within the United Nations Framework Convention on Climate Change, potentially under a climate agreement such as the Kyoto Protocol. For example, a national emissions trading scheme could be linked to the international carbon market, meaning that any credited emissions reductions achieved in China could be sold on the carbon market. China has been very active in the Kyoto Protocol's Clean Development Mechanism (CDM), boosting 3,500 registered projects, accounting for approximately 70% of the total carbon credits generated in Asia (with Asia accounting for 80% of all carbon credits generated under the mechanism to date) [57].

However, the future of the Kyoto Protocol, and thus the motivation to harmonise climate policies for the purposes of linking mechanisms internationally, is currently unclear. Nationally Appropriate Mitigation Actions (NAMAs) and New Market Based Mechanisms (NMBMs), such as sectoral crediting/trading schemes, are being discussed within the UNFCCC as potential follow-ups to the Clean Development Mechanism, and these mechanisms could incentivise technologies such as CCUS. One potential barrier foreseen within Chinese climate policy is the focus on emissions intensity and taxes on resource use, rather than on absolute emissions, which have been the primary metric used within policy making in other countries.

5. Public Perception and Acceptance

5.1. Health and safety issues

The general public are relatively unaware of CCS, the risks involved and the nature of CO_2. Initial reactions to the technology are usually sceptical but have a tendency to improve when information is provided. A distinction may be drawn between the general views of CCS of the public and those of local opposition to particular projects, which in the past has been strong enough to lead to significant disruption and postponement of CCS projects [58]. Negative opinions to CCS can be influenced by perceived risks of O_2 leakages from pipelines or storages, either gradual or catastrophic, which might impact on the environment, ecosystems and human health, the possibility of induced ground motion which could damage buildings and the possibility that sequestered CO_2 could contaminate water supplies [59]. Uncertainties concerning the potential risks of CCS, especially the risks of accidents and leakage, should be addressed in order to reassure the public. There have been very few studies on public perception on CCS in China, whereas there have been a few covering stakeholder perceptions. Surveys conducted by Duan [60] found slight support for CCS amongst the Chinese public but local opposition to CCS projects should still be expected in China just as in any other country. Stakeholder perceptions of Health and Safety concerns surrounding CCS also extend to coal mining accidents [61].

Barriers of low public acceptance for CCS can be overcome through information and education on human caused climate change and the recognition of the need for major CO_2 reductions. Acceptance of CCS can also be aided when it is seen as part of a wider strategy in the energy portfolio for cuts in CO_2 emissions. [62]

5.2. Visual impact

The burial of CO_2 pipelines is a possibility if the diameter is not too large – this could lead to a significant reduction in visual impact of CCUS projects. However, significant visual impact along pipeline routes could still occur during the commissioning and decommissioning stages. Local concerns about visual impact of equipment should be taken on board and designs adjusted accordingly where possible.

5.3. Financial issues

Further barriers to public acceptance can relate to the costs of CCUS deployment and plans for its use for a relatively short period of time. International funding of CCUS projects could help to alleviate public financial concerns. In the survey by Duan [60], over half the Chinese respondents were concerned that the government's support for CCS could divert funds and investment from other clean energy technologies and renewable energies. However, early opportunity projects that utilise CO_2 for a purpose like EOR and ECBM would appear more financially attractive in comparison to capture from the power energy sector, which has associated energy penalties and incremental energy price increases. The increased fuel productions from CO_2-EOR and –ECBM projects could help to sway public opinion on financial issues.

6. Recommendations

Based on the gaps and barriers of CCS technologies, we recommended that:

1. **Listing CCS into China's future science development plan.** The main barrier of developing CCS is the uncertainty of the strategy. We suggest making a CCS development strategy plan and listing CCS as our frontier technology in energy, environment and other related areas in the future.
2. **Supporting CCS theoretic and technological research.** Starting from the basic theoretic research and technological revolution, initiate the council's major research plan, extract key scientific problems and implement basic theoretic research on greenhouse gas control and CCS. Supported by the Ministry of Science and Technology (MOST) supporting plan and '863' project, clarify the technology puzzles, implement CCS R&D with low energy penalty and low cost, and make CCS standards and regulations for the project implementation.
3. **Implementing CCS demonstration project.** Form a government supported and enterprise mainstay regime to coordinate interests among industries, implement demonstration projects, accelerate the transfer of scientific achievements and realise the combination of scientific and industrial plans. Use foreign funds to support CCS demonstration projects and make sure that the nation's fund takes a substantial proportion of the total investment to mitigate the enterprise's risk and responsibility.
4. **Building CCS technological platform and strengthening international cooperation.** Form a national low carbon technology research center and an alliance between industry, academia and the research community to make CCS key technology breakthroughs. Strengthen international cooperation in low carbon revolution areas, and build an international regime with low carbon technology R&D, competition and optimization.

5. **The project strongly recommends that (at least) the first demonstration project should be a national programme**, conducted by a consortium of complementary partners and led by a pioneering company, such as Greengen, with government support. The learning and experiences gained during demonstration can be accessed by all interested enterprises. Chinese enterprises have started taking actions in CCS research and development. However, there is an absolute necessity for strong government leadership to form a national CCS consortium. A demonstration project should be a horizontally integrated project along the CCS value chain in order to combine strengths and reduce weaknesses substantially. Such integration could be achieved through either signing long-term contracts among participating companies in capture, transportation and storage along the CCS value chain or establishing a joint venture among shareholder companies to share risk among different companies.
6. China has an opportunity to observe and draw lessons from the experiences of other countries in deciding how it wants to proceed in developing regulations. At the same time, it is important to recognise that these regulatory frameworks are being prepared by nations that expect to establish a legal basis for the commercial deployment of CCS. A new set of policy options are needed at the national level to address technical, institutional, legal, regulatory and financial gaps, promote demonstration projects with a standardised approach that provides replicable cases for future projects. Policy options at the national level have important implications not only for CCS at the national level but also for demonstration projects at project level.

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Executive Summary

Capturing CO_2 from processes that have low concentrations of CO_2 in the flue gases is associated with high investment and energy costs. CO_2 emissions from coal and gas-fired power plants normally have a CO_2 concentration in the flue gas of 8–15%, whereas certain industrial processes such as hydrogen, ammonia and methanol production can have CO_2 concentrations of between 50% to almost 100%. This study has identified a number of high purity sources in the Shaanxi province, with high-purity streams of CO_2 estimated to be approximately 45 mega tons per year.

1. Introduction

1.1 Introduction to CCUS

Carbon capture and storage (CCS) refers to technology that can prevent the release of large quantities of CO_2 into the atmosphere from fossil fuel use in power generation and other industries by capturing CO_2, transporting it and ultimately, pumping it into underground geologic formations to securely store it away from the atmosphere [1]. It is a potential means of mitigating the contribution of fossil fuel emissions to global warming.

According to the state condition of China, the CCUS concept (carbon capture, utilisation and storage) is proposed. Based on CCS, the CO_2 utilisation process is added, including enhanced oil recovery (EOR), Enhanced Coal Bed Methane recovery (ECBM), in food industry etc.

1.2 Objective of this report

Since coal plays an important role in China’s energy structure, as an important option to mitigate CO_2 emissions, CCS is promising in China. However, some barriers to CCS demonstration include: (1) the identification of the potential cost-effective CCS chain; (2) the identification of the funds to support the CCS demonstration; (3) difficulty in coordination of the whole CCS chain covering different industries; and (4) lack of government coordination through industrial policy, regulations and incentive policies will result in prohibitively high cost of initial CCS demonstration projects and is likely to delay further development of potentially cost-effective CCS projects in China.

Preliminary work on CCS in China has focused on CCS in the power sector. However, CO_2 capture from power sector is energy-intensive and expensive due to the low CO_2 concentration in the flue. It is easier to realise CO_2 capture at a lower cost at large point sources with high-purity CO_2 in non-power sector, such as in fertiliser plants, coal-to-liquids facilities and refineries. China has a large industrial base in these sectors, resulting in a significant CO_2 emission reduction potential through CCS.

This project also aids to identify and build CCS demonstration in non-power sector and helps to overcome the barriers of project deployment.

1.3 Methodology and introduction to the outline

In the project, the high-purity CO_2 sources in non-power sector and the potential CO_2 sinks in Shaanxi Province will be identified, the mating of CO_2 sources and sinks will be done and the CCUS demonstration in Shaanxi province will be recommended. Also, the gaps and barriers, funding sources of the CCUS will be identified and recommended.

2 Industrial processes with CO_2 emissions

In 2006, the overall emissions of CO_2 in China were 5000 million tons per year and it is expected that the total emissions in 2012 will be over 7000 million tons per year. The main industries that produce CO_2 emissions are fossil fuel power plants, oil refineries, and gas processing plants, ammonia plants, steel plants, ethylene production, ethylene oxide production, hydrogen production, cement production plants and others.

Figure 2.1 shows the CO_2 emissions in the different industries of China in 2004. It can be seen from the figure that the CO_2 emissions from power plants were around 1863 million tons, accounting for nearly 63% of the total emissions in 2004. The power plants were the primary sources of CO_2 emissions followed by the emissions from cement and steel industries, whose emissions were 570 and 282 million tons individually. In recent years, with the growth of the installed capacity of China's power plants, steel and cement production, the total CO_2 emissions have shown a continuous upward trend. The installed capacity of fossil fuel power plants in China was more than 70% of the total installed power generating capacity, which was 390 million kilowatts in 2005, and the CO_2 emissions from these power plants were around 2200 million tons per year. With the economy booming and the demand for energy growing in 2010, the installed capacity of fossil fuel power plants rose rapidly to 700 million kilowatts, which caused CO_2 emissions to increase by around 4000 million tons per year, compared to 2005 the number of which was almost doubled. The CO_2 emissions from China's power industry in recent years are shown in Table 2.1.

It is estimated that the installed capacity of fossil fuel power plants will still maintain growth until 2030, and the related CO_2 emissions will continue to increase as well. Because of the continuous acceleration of urbanisation and infrastructure construction, China's cement demand, and therefore production, continues to grow. China's cement output was about one billion tons in 2005, while in 2010 it had climbed to nearly two billion tons. At the same time the CO_2 emissions in the cement industry increased from about one billion tons/year to about two billion tons/year. The cement industry's CO_2 emissions are shown in Figure 2.2 (2).

Meanwhile, China's steel production in recent years has also steadily increased, with a corresponding increase in related CO_2 emissions. China's steel production in 2005 was 355 million tons, and it jumped up to 489 million tons in 2007 and 650 million tons in 2010. China's steel production is expected to grow further along with the further deepening and development of China's construction industry. It was estimated that the steel industry's CO_2 emissions in 2010 was around 820 million tons per year, and it is expected to continue to expand over the next decade.

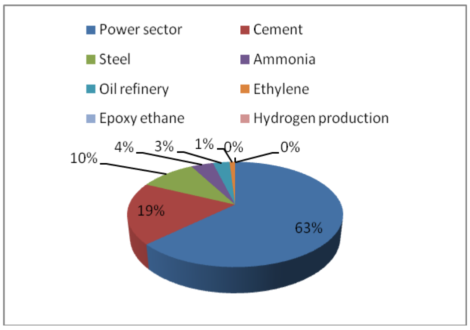

Figure 2.1 CO_2 emissions of different industries in 2004 in China [2]

Table 2.1 CO_2 emissions from fossil power plants in recent years in China

Year	Installed capacity (0.1 billion kilowatts)	CO_2 emission (0.1 billion tons /year)
2002	2.66	14.89
2003	2.90	16.25
2004	3.29	18.47
2005	3.91	21.94
2006	4.84	27.14
2007	5.50	30.84
2008	6.01	33.71
2009	6.52	36.56
2010	7.00	39.24

Source: China's state Statistics Yearbook, State Electricity Regulatory Commission.

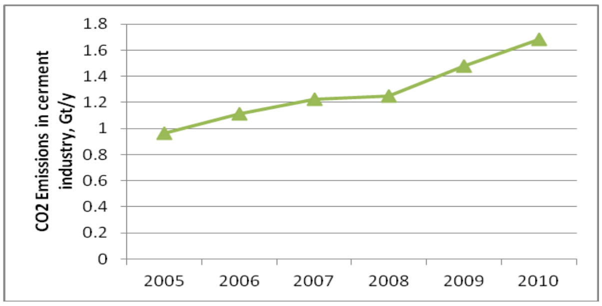

Figure 2.2. CO_2 emissions from cement industry in China

Table 2.2 lists the CO_2 concentration in the typical industrial processes. Among these processes, some chemical processes, such as ammonia, ethylene oxide, hydrogen production processes need CO_2 removal as an integral part of the process, so the CO_2 concentration of such emissions from these processes is much higher. The CO_2 concentration in the cement industry and steel industry is about 20%, while in the thermal power plants it is relatively lower, at about 10–15%.

Table 2.2. The CO_2 concentration of different CO_2 sources

Emission sources	Typical CO_2 concentration,%
Coal fired power plant	10-15
Cement plant	20
Hydrogen plant	50
Ethylene plant	12
Steel plant	20
Oil refinery	8
Epoxy ethane	99.9
Ammonia plant	99.9

2.1. The impact of CO_2 purity on energy/economic penalty

Energy costs are key factors to impact the success and future development of CCS demonstration projects. The concentration of CO_2 in the gas to be separated is the key factor to affect the energy consumption of CO_2 separation and the CO_2 capture costs. Energy consumption of CO_2 separation is determined by two factors: (1) ideal work or alternatively called the minimum separation work for CO_2 separation in an ideal process; and (2) the energy efficiency of CO_2 separation in the actual separation process, which is defined as the ratio of actual separation work to the ideal separation work. The ideal separation work only relates with the thermodynamic state before and after the separation, and the separation efficiency depends on the level of energy utilisation in the specific separation process.

The formula of the ideal separation work for CO_2 separation is shown in Eq. (1).

$$\begin{aligned} E_{idea} &= R \cdot T_0 \cdot \frac{X \cdot (1-K) \cdot \ln\left[X(1-K)\right] - (1 - X \cdot K) \cdot \ln(1 - X \cdot K) - X \cdot \ln(X)}{X \cdot K} \\ &= f(X, K) \end{aligned} \qquad \text{Eq. (1)}$$

Where, E_{idea} is the ideal work for CO_2 separation, X is CO_2 concentration, and K is the recovery rate. As it can be seen from the formula, the independent variables to determine the ideal separation work of CO_2 separation process is the CO_2 concentration X in the gas and the CO_2 recovery rate K.

On the basis of the expression of ideal separation work for CO_2 separation, the formula of actual energy consumption is shown as follows:

$$H = E_{idea} / \eta_{sep} \qquad \text{Eq. (2)}$$

Where, η_{sep} is the efficiency of CO_2 separation for the actual separation process.

Figure 2.3 shows the relationship between the separation work and CO_2 concentration. It can be seen that the higher the CO_2 concentration, the smaller the separation work. When the concentration is less than 20%, with the reduction of CO_2 concentration, CO_2 separation work will rapidly increase.

From this analysis we can draw the following conclusions:

- To reduce the energy consumption of CO_2 separation, one of the key factors is to enhance the CO_2 concentration before separation.
- As CO_2 concentration differs in different points of each industry process, choosing the reasonable separation point is the first step to achieve low energy for CO_2 separation.
- We can improve energy utilisation levels (increasing the separation efficiency, e.g. to select advanced CO_2 separation technology or to adopt new absorbents) in the separation process to reduce the CO_2 separation energy consumption eventually.

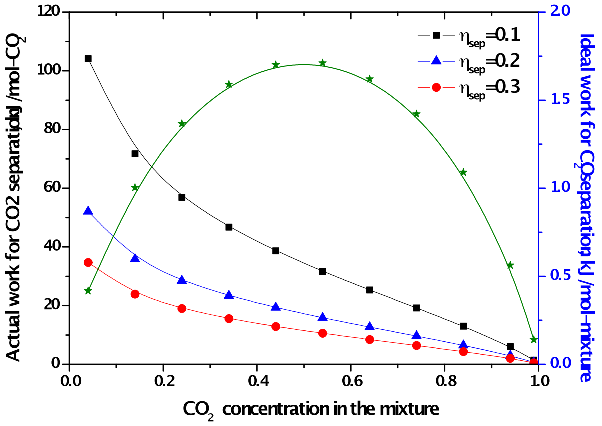

Figure 2.3. The relationship between energy consumption for CO_2 separation and the CO_2 concentration

The CO_2 concentration not only affects the energy consumption for CO_2 separation, but also directly affects the CO_2 capture cost. The cost of CO_2 capture is mainly composed of two parts: the extra cost of equipment investment, and the cost of fuel for CO_2 separation. Among them, the extra cost of equipment investment directly relates to the gas volume (the volume of the gas determines the scale of the equipment), which means that in the conditions of a fixed CO_2 separation amount (the CO_2 capture rate is fixed), the extra cost is directly related to the CO_2 concentration in the gas mixture. The cost of fuel needed for CO_2 separation is proportional to the energy consumption for separation. Therefore, the concentration of CO_2 is an important factor affecting the cost of CO_2 capture.

The main three technologies for CO_2 capture are:

Pre-combustion separation

If we choose to capture CO_2 before combustion, the CO_2 concentration can reach 20-30% and to capture 90% of the CO_2 will make the energy system's efficiency drop by 7–10 percentage points and the CO_2 capture costs will be around $25-45/t.

Oxygen combustion

In the oxygen-combustion capture technology, although the concentration of CO_2 is high (often higher than 80%). The high concentration of CO_2 is acquired at the price of additional energy consumption for producing oxygen from air separation unit, and thus to capture 90% of the CO_2 will make the energy system's efficiency drop by 8–10 percentage points, and the CO_2 capture costs are about 30-50 $/t. The concentration of CO_2 in the exhaust of coal-fired power plants is 10–15% in general, and is even lower (around 3–5%) in the exhaust from the natural gas power plant.

Post-combustion separation.

To separate 90% CO_2 by post-combustion, the efficiency of the power system will be reduced by 10–15 percentage points, and the CO_2 capture cost will be around 40-60 $/t. The relationship between CO_2 concentration and the capture cost is shown in Figure 2.4.

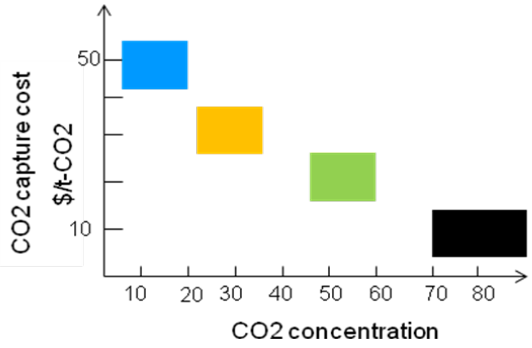

Figure 2.4. The relationship between CO_2 concentration and the capture cost

2.2 Definition of high purity CO_2 sources in industrial processes

The use of high-purity CO_2 sources removes one of the most important barriers to CO_2 capture and storage: the high-energy use and costs of CO_2 removal from diluted process streams. High-purity CO_2 sources can be defined as those streams from which CO_2 does not need to be separated, but that can directly be applied for CO_2 utilisation and/or storage, only requiring compression and removal of water and minor impurities.

These streams are encountered in many cases in industry because some industrial processes require a CO_2 removal step from which high-purity CO_2 is produced. The CO_2 in the process stream is part of the feed gas or it is formed as a (by)-product in conversion of fossil fuels such as oil, coal or natural gas. The removal of CO_2 from the industrial process is required to purify the product, or because the CO_2 has an adverse effect on downstream steps in the industrial process. Since this CO_2 removal step is necessary in the industrial process, its costs are not attributed to CCUS. This largely reduces the investments and operating costs for CCUS, since the largest contribution to the costs of CCUS are those of CO_2 separation.

The criteria for the classification of the CO_2 concentration differ a lot between industries and plants, and there are no unified or authoritative criteria for the classification until now. It is known that energy consumption and cost of CO_2 separation are the most important factors affecting the CCS development, while the concentration directly affects the energy consumption and cost.

In this report, the CO_2 concentration levels are classified based on the influence of the CO_2 concentration on the energy consumption. As shown in Figure 2.3, when the concentration of CO_2 is less than 20%, with the concentration changing, the energy consumption of separation CO_2 changes very sharply. Once the concentration drops by five percentage points, energy consumption for CO_2 separation will increase by 5–17 kJ/mol (separation efficiency is assumed to be 0.1 here and afterwards), so this report defines the emission sources with CO_2 concentration less than 20% as emissions sources of low CO_2 concentration.

When the CO_2 concentration changes in the range of 20%–50%, along with the concentration change, the change of energy consumption for CO_2 separation changes is slowing down. In this interval, for each drop of five percentage points in CO_2 concentration, the energy consumption increases by 3.5-5 kJ/mol, and thus this report defines CO_2 emission sources in this concentration range as the moderate concentration emission sources.

When the CO_2 concentration changes in the range of 50%–90%, the energy consumption for CO_2 separation showed a linear decline with the increase of its concentration, which is not that obvious. For each drop of five percentage points in concentration, the energy consumption for CO_2 separation increases by 3-3.5 kJ/mol, and therefore we define this concentration interval as the secondary highest CO_2 concentration range. When the CO_2 concentration is higher than 90%, the energy requirement for CO_2 separation becomes very small and, in these cases, CO_2 can be captured by simple processes. The CO_2 emissions sources, whose concentration is higher than 90%, are defined as the high concentration CO_2 emissions sources. The classification for CO_2 emissions sources of different concentration is shown in Table 2.3.

Table 2.3: The classification criteria for CO_2 emissions sources of different concentration

CO_2 concentration in emissions source (%)	Concentration level
>90	High
50-90	Secondary highest
20-50	Moderate
<20	Low

2.2.1 Separation processes providing high-purity CO_2 sources

The four main categories of obtaining high-purity industrial CO_2 removal streams are chemical solvents; physical solvents; pressure swing adsorption (PSA); and membranes and other technologies, which are discussed briefly below.

Chemical solvents are water soluble components that remove the CO_2 from a gaseous process stream by forming a chemical bond with it. This is carried out in an absorption tower, after which the CO_2 loaded solvent is transported to a stripping tower where the CO_2 is released by adding heat. Chemical solvents are capable of removing CO_2 from low concentration or low pressure gases, but have the disadvantage of a relatively high energy demand for regeneration. Because of the highly selective chemical reaction, the resulting CO_2 stream is very pure. Commonly used physical chemical solvents are MEA (mono-ethanolamine), MDEA (Methyldiethylamine), Sulfinol and potassium carbonate solution [3].

Physical solvents are liquids that remove CO_2 by physical absorption of the CO_2 into the liquid. This is carried out in an absorption tower. The CO_2 loaded solvent flows to a stripping tower where the CO_2 is released at elevated temperature. The resulting CO_2 stream is pure but some co-absorption of gaseous components may occur. Physical solvents require a high CO_2 pressure, a combination of a high feed pressure with a sufficient CO_2 concentration. Their advantage is a relatively low regeneration heat compared to chemical solvents, though some solvents require refrigeration. Commonly used physical solvents are Rectisol (methanol), Purisol and Selexol [3]. A novel technology currently under investigation is the use of chilled ammonia.

Both chemical (e.g. Selexol) and physical solvents (e.g. Sulfinol) are used for simultaneous removal of H_2S, and in some cases other sulphurous components (COS, mercaptanes) with the removal of CO_2. In some cases (e.g. for Selexol) it is possible to design the removal process in such a way that a relatively pure CO_2 stream is obtained, next to a stream that contains the H_2S diluted with CO_2.

PSA or pressure swing adsorption is a gas/solid process in which the CO_2 (often together with other components) is physically adsorbed at high pressure from a synthesis gas on a solid phase sorbent. After fully loading the sorbent in a batch-wise process, the CO_2 is then released by reducing the pressure. PSA is a very effective way of removing CO_2 and other components, thus having the advantage of producing a very high-purity H_2 stream combined with having low energy demand. However, PSA is not suitable for obtaining a high-purity CO_2 stream. Typically the CO_2 will contain 20–30 % by volume of components like H_2, CO and CH_4, which are sent to a furnace to make use of the heating value of these components. Other uses of this stream require significant changes to its handling, which is an additional barrier to CCUS [4].

Lastly, **membranes** are used for CO_2 (and H_2S) removal in natural gas production, especially in cases where compact equipment is required, such as on gas platforms. The polymeric membranes used have a limited selectivity so the CO_2 produced will contain significant amounts of CH_4 and H_2S if present in the gas. The use of membranes will be discussed later in the natural gas processing section.

Emerging and alternative technologies for CO_2 separation include the use of high-temperature hydrogen separation selective, high-temperature CO_2 sorbents, CO_2 freezing out or cryogenic separation and several types of novel solvents [3] [5]. Most of these technologies are less relevant for short-term application in existing facilities.

2.2.2 Specifications and impurities

The specifications for CO_2 purity may be set by considerations on compression, transport and underground storage. How pure the CO_2 needs to be depends on the impurity considered and CO_2 application. Table 2.4 lists some of the effects limiting the impurity level of CO_2 streams.

Table 2.4: Considerations limiting the impurity level in CO_2 streams, adapted from [6]

Component	Limited by
Nitrogen	MMP*, Compression costs
Hydrocarbons	MMP
Water	Corrosion
Oxygen	Corrosion, storage reservoir issues (EOR)
H_2S	Health and Safety
CO	Health and safety
Glycol	Operations
Temperature	Material integrity

*MMP=Minimum Miscibility Pressure.

Currently there are no national or internationally agreed standards for CO_2 purity. Specifications have been developed by research projects [7] [8] [9]. A possible set of specifications is listed in Table 2.5. Depending on project-specific aspects, CO_2 specifications may be adapted.

Table 2.5: CO_2 specifications [9]

	Recommended by EBTF	**Aquifer**	**EOR**
CO_2	> 90 vol	% > 90 vol	% > 90 vol %
H_2O	< 500 ppm (v)	< 500 ppm (v)	< 50 ppm (v)
H_2S	< 200 ppm (v)	<1.5 vol %	< 50 ppm (v)
NO_x	< 100 ppm (v)	NA	NA
SO_x	< 100 ppm (v)	NA	<50 ppm (v)
HCN	< 5 ppm (v)	NA	NA
COS	< 50 ppm (v)	NA	< 50 ppm (v)
RSH	< 50 ppm (v)	NA	> 90 vol %
N_2, Ar, H_2*	< 4 vol % *	< 4 vol % *	< 4 vol % *
CH4	< 2 vol %	< 4 vol % *	< 2 vol %
CO *	< 0.2 vol %	< 4 vol % *	< 4 vol % *
O2	<100 ppm vol	< 4 vol % *	<100 ppm vol

NA = Not available

Note: * - $x + \Sigma xi < 4$ vol % = total content of all non-condensable gases

Next to the quality of the CO_2 there needs to be an alignment between the need for amount of CO_2 for EOR in terms of flow rate and supply/demand time related characteristics.

The maximum CO_2 demand for a typical EOR operation will vary with the size and characteristics of an oil field. Typical CCS-EOR projects store between 0.5 and 9 mega tons (Mt) of CO_2/year, with a typical value of around 1.0 Mt/year. EOR projects involving natural CO_2 sources may even much be larger, up to 32 Mt/year CO_2 [6]. The demand for a CO_2 EOR operation is however not constant and will change over the course of a project. Typically, the need for CO_2 increases during the first years goes through a maximum and decreases due to recycling of CO_2 that is produced with the oil, see Figure 2.5.

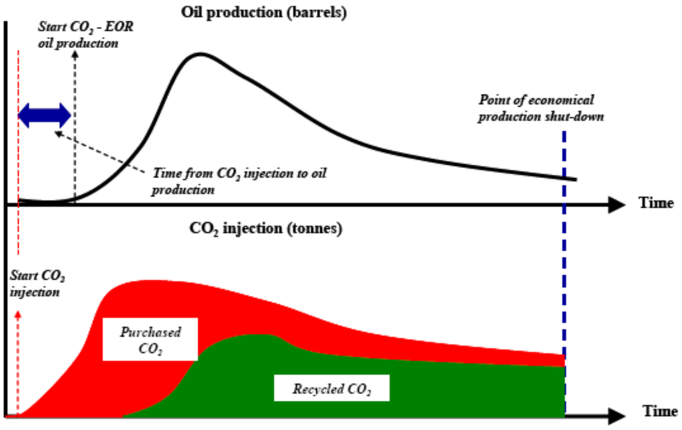

Figure 2.5: Oil production and CO_2 demand injected over the course of an EOR project [10]

2.2.3 Compression and after-treatment

CO_2 for EOR is compressed in a multi-stage compressor/CO_2 pump combination equipped with inter-cooling and water removal. The resulting CO_2 stream is in the super-critical state. A commonly used suitable pressure for transport is 110 bar.

The product cooler cools the CO_2 down to a temperature less than 30°C. During compression most of the water is already removed. Further water removal can be achieved using glycol drying or with mole sieves if a very low water content needs to be met.

Typical for EOR operations is a very low limit for oxygen. Small amounts of oxygen can be mitigated using a catalytic oxidation unit (CATOX). Large amounts of oxygen may be removed by cryogenic separation in the compression section. During compression also SO_x and NO_x may be reduced by water-phase reaction and by cryogenic distillation.

2.3. Description of high purity CO_2 sources in industrial processes: chemical production/cement production

Industry sectors that are interesting for CCUS, because of the magnitude of their CO_2 emissions, are listed in Table 2.6. Though many of these industries have high emissions, those interesting for early applications are much less because of the high dilution of the CO_2 stream. Industries that have high-purity streams for early opportunities can be found only in the gas and oil industry, in ammonia industry, and in biomass conversion.

Table 2.6 Current technologies producing high-purity CO_2 for early CCUS opportunities

Industry	Technology producing high-purity CO_2
Power production	-
Gas and oil industry	Natural gas processing LNG production Coal-to-liquids Gas-to-liquids
Chemical industry	Ammonia/Urea production (Poly)Ethylene production
Biomass conversion	Biomass to Liquids Bioethanol production
Cement industry	-
Iron and steel industry	-
Refineries	-

2.3.1. Natural gas processing

Natural gas typically undergoes processing before it can be fed to the natural gas grid. Depending on field conditions it may contain 2%–70% of CO_2 that needs to be removed to a large degree to meet pipeline specifications. Removal is done by conventional technologies such as amine (MDEA) scrubbing. This gives a high-purity CO_2 stream available for CCUS. Processing plants using membrane gas separation do not produce a sufficiently pure CO_2 stream.

In the past decades Chinese natural gas production has grown rapidly. In the Shaanxi Province, natural gas production has a large proven reserve of natural gas (70 billion m^3 in west area of

Shanbei and 3.3 billion m^3 in Hengshan and Yulin areas [11]. However, there is little information on the natural gas specifications and treatment required. Detailed case studies involving the gas field operators are needed to assess whether CO_2 removal is necessary for the gas produced in these reserves and whether the CO_2 is of sufficient quality and flow rate to be amenable for utilisation or storage.

2.3.2. Coal-to-liquids

Coal-to-liquids (CTL) is a group of technologies in which liquid fuels/base chemicals are produced from coal. The main technology currently pursued replaces current common liquids such as gasoline, diesel and naphtha, though also alternative fuels such as gaseous hydrogen and dimethylether are possible products [12]. Though it is not a very significant industry today, CTL could grow fast in the near future. The main drivers include prices of oil and security of liquid fuel supply, as for CTL, China can use domestic coal as a source [13]. In spite of now becoming a net importer of coal, China coal reserves are still much larger than oil.

Another rationale for coal-to-liquid technology is that liquid fuels contain less CO_2 per unit of energy, so emission reductions could be achieved if the CO_2 produced from the conversion is stored underground or used [14]. Indeed CCUS can largely reduce the CO_2 emissions from the process itself – however, the liquids produced still contain fossil carbon which is emitted eventually in the form of CO_2. Therefore taking into account the whole fuel chain, not all emissions are reduced by far, even when CCUS is applied at the conversion plant. When applying CCUS with coal-to-liquid technology, the emissions of the fuel chain are comparable to that of conventional liquid fuels [15]. Therefore CCUS can be considered a technology of increasing the security of supply of liquid fuels while avoiding a drastic increase in emissions. Financially, high oil prices will stimulate the development and implementation of CTL technology. Local governments may stimulate development of CTL projects using local coal reserves. The National Development and Reform Commission (NDRC), which has to approve all CTL projects, however has so far been reluctant in granting permits [16].

The many existing CTL technologies can be classified into two main categories: direct and indirect conversion [17]. Both technologies offer early opportunities for CCUS. Indirect conversion uses gasification with subsequent partial CO_2 removal and liquids production from the gas. The other technology is indirect coal conversion where the coal is cracked into crude oil products using high temperature, pressure and a catalyst. The cracking process as well as the required upgrading step of the liquid products uses hydrogen that is produced from coal gasification with CO_2 removal. Products are heavy oil, naphtha, diesel and LPG. Around 80% of the CO_2 produced in this step can be stored without additional capture costs.

In China, the Shenhua group is very active in CTL technology development and has constructed a ‘Coal Liquifaction Production Line’ in the Ordos region, Inner Mongolia [14] [13] [18] [19]. The facility is built for development of direct coal liquefaction technology. Start-up was in December 2008 and by July 2011 over 10,000 cumulative production hours had been achieved. CO_2 is produced with membrane technology – for CCUS, the CO_2 concentration will be increased from 87% to above 95%, while capturing 85% of the CO_2 emitted. The facility will be able to capture and store 100 kton CO_2 /year.

When a full scale facility is built, it is expected to produce nearly 1 Mton of oil products per year, equivalent to approximately 25,000 barrels of oil per day. The estimated total cost of the first phase of the plant is $1.5 billion US. The plant will also produce nearly 3.4 Mton/year of CO_2 of which 3 Mton/year can be used for storage without additional capture costs.

Shenhua company is investigating the possibility of storing this CO_2 in the Ordos Basin. For the development facility aquifer storage is considered but for the full scale facility, different methods of storage can be considered, including EOR and Enhanced Gas Recovery (EGR), but also storage in saline aquifers. Alongside this, unminable coal seams may be available for storage combined with enhanced coal bed methane recovery (ECBM).

In the Shaanxi Province several initiatives for the development of CTL installations have been taken. In 2007, Dow and Shenhua announced plans for a direct CTL plant at the Yulin chemical plant [20] and Yankuang Group is planning a 5 Mton/year indirect CTL facility in Yulin, with a first phase of 1 Mton/year output. However, this project has been suspended following a notice of the NDRC in 2008 [21] [16].

2.3.3. Biomass conversion

The CO_2 emitted from biomass or biomass-based product can be considered climate neutral since this is based on short-cyclic carbon, originating from CO_2 captured from air relatively shortly before combustion during growth of the biomass. Therefore, by using biomass the amount of CO_2 in the earth atmosphere is kept constant.

An interesting option is combining biomass use with CCS to BE-CCS (bio-energy with CO_2 capture and storage). Here, ‘negative emissions’ can be achieved; effectively CO_2 is captured from the earth’s atmosphere by the biomass, captured by the biomass processing, and then stored underground. Such technologies are interesting if very aggressive emission reductions are required, but these technologies could also be used as early opportunities for CCUS demonstrations [22].

Biomass can be used to produce electricity, hydrogen, liquid and gaseous fuels and chemical products. Thermal conversion technologies involve combustion and gasification. Of these, the latter is most interesting since this results in a synthesis gas stream from which CO_2 can be captured at low cost. These are very similar to coal-to-liquid technologies, only the coal fuel is replaced by biomass from pre-treated woody sources [23] [22]. Coal and biomass can also be converted together (CBTL), reducing the environmental impact of CTL [24].

Fermentation technologies of interest are currently first-generation bio-ethanol production processes using mainly maize, wheat and cassava. Of the carbon feed that leaves the plant, 67% is as ethanol and the remaining 33% of the carbon becomes available as highly pure CO_2 stream, suitable for CCUS. Multiple bio-ethanol plants in the USA currently supply CO_2 for underground storage projects. At present, China is the world's third largest producer of bio-ethanol – in 2007 there were five bio-ethanol plants with a total yield of 1.5 Mton/year. None were in the Shaanxi Province, but one is in the neighbouring province of Henan. Further growth may at some point be limited by competition with land for food production, and there are serious concerns on that. Development of second generation biofuel technologies based on non-grain sources may overcome this direct competition with food, but the issue of land use remains [25] [26].

2.3.4. Ammonia/fertiliser production

Ammonia is manufactured from natural gas, oil or coal. In contrast to the rest of the world, where natural gas is the main feedstock, in China the main feedstock is coal/cokes (71%) followed by natural gas (21%) and oil (8%) [27]. Total Chinese emissions amounted to 181 $MtCO_2$ in 2005. China also has a relatively large amount of small and medium scale ammonia plants; around 82% have a production capacity of less than 300,000 tons/year, while CCUS is mainly suitable for large-scale plants. In these large-scale plants, the feedstock is converted by reforming or gasification into a synthesis gas stream from which all CO_2 needs to be removed. If this is done by liquid-phase chemical adsorption, a highly pure CO_2 stream is provided which may be used for CCUS. However, some processes make use of PSA, which does not produce a sufficiently pure CO_2 stream. Ammonia production is carried as a continuous process out at large scale (typically 10 Mt NH_3/year) making it an attractive option for large-scale demonstration of CCUS.

In about half of the plants in China the CO_2, or part of the CO_2, produced is further converted into ingredients for fertilisers such as urea and ammonium bicarbonate. In 2008 this amounted to a total use of 18 Mton. Strictly speaking, this is in itself already a form of CCUS, but is often not considered at such because it is not a climate related activity that is additional to common industrial practice. In the case of natural gas as a feedstock, most or all of the CO_2 separated from the syngas stream can be used in urea production. Using coal or oil as a feedstock gives more CO_2 production than can be processed in the urea plant. For these feedstocks, typically about half of the CO_2 separated is used in urea production. Some plants make use of separation using PSA – in these cases the CO_2 stream will contain inert compounds that mean that the stream is not pure enough for CCUS. Also, it could contain H_2S, which for some storage options such as EOR or other specific storage/usage, may not be acceptable. Therefore, the viability of CCUS needs to be assessed also on a case-by-case basis looking at the process feedstock, separation processes and stream purities, and also judging the relative size of ammonia plant relative to the associated urea plant.

Taking these factors into account, one study [28] concluded that in 2007 China had six coal-fed and eight oil-fed modern gasifiers that were suitable for downstream CO_2 removal for CCUS. In 2004 another 10 units were planned.

One potential site located in the Shaanxi Province is at the Weihe Chemical Fertiliser Company in Weinan. It concerns a coal-fed ammonia plant with two Texaco coal-fed gasifiers (and one spare) with a fuel input of 273 MW_{th}. The plant produces 948 $ktCO_2$/year, of which 381 $ktCO_2$ is used for urea production, resulting in 567 $ktCO_2$/year being available for CCUS. A process scheme published by [29] shows that the process uses methanol physical adsorption producing separate H_2S and CO_2 streams, making it likely that the CO_2 is of sufficient quality for CCUS.

In a study by IEA GHG [30] a worldwide survey for early opportunities for CCUS was conducted in which here again the Weihe Chemical Fertiliser Plant was listed as a potential candidate for CO_2 supply, using the CO_2 in Hedong-Weibei coal-bearing region for coal-bed-methane. Another CO_2 source listed in Shaanxi was the Shaanxi Chemical Industry group fertiliser plant. This plant produces 677kt CO_2/year and operates 8000 hrs/year. CO_2 could potentially be used for two applications. The first, selected by the authors, was for coal-bed-methane in the Eastern Piedmont of Tanghai Mts. coal basin at a distance of 50km. This area is one of the nine coal bed methane blocks approved for exploitation through foreign co-operation by the Chinese government. An economic evaluation indicated net sequestration costs of 13 €/tonCO_2 based on 32 €/tCO_2 for CO_2 and coal-bed-methane costs, and 19 €/tCO_2 of methane revenues. The same study concluded that EOR gives a net profit as a result for typically lower cost and higher revenues. Another option for storage of Shaanxi Chemical Industry group fertiliser plant was studied, but in far less detail. This option was EOR in the tertiary Lacustrine of the Bohaiwan Basin. However, no detailed study was made here.

2.3.5. Ethylene production

Ethylene is one of the most important building blocks in the chemical industry, with a yearly production capacity in 2012 of 13 Mtons/year. The main way of producing polyethylene is by cracking of oil fractions to yield a product with ethylene, CO_2, methane and other hydrocarbons. From this product stream CO_2 is removed using a liquid phase chemical absorption using a Benson tower. From the resulting stream ethylene is recovered and the other products are either recovered or recycled. The resulting CO_2 stream is of high purity and suitable for CCUS [31]. Though relative amounts of CO_2 produced are rather high (1-1.6 tonCO_2/ton$_{ethylene}$), CO_2 emissions from most existing plants are rather small, typically 150-250 kt/year. This means that ethylene plants are restricted to small projects with relative higher costs unless these can be combined with other CO_2 sources [5].

An alternative way of producing ethylene of interest in China is the new MTO process (methanol to olefins), which uses coal rather than oil fractions as a feedstock. Here, first methanol is produced which is then converted into ethylene. In the methanol production step CO_2 can be removed.

China's ethylene production capacity is growing extremely fast. Production is expected to grow by 44% (5.85 Mt/year) to 19.08 Mt/year as of 2013. After that, growth is expected to slow down under macro control of the government [32].

In Shaanxi Province, construction of a large MTO plant is planned in Yulin to produce 500,000 tons/year of ethylene. The project by Shenhua Group/Dow Chemical is expected to commence operations in 2016 [32]. China Coal Shaanxi Yulin Energy & Chemical Co. Ltd has also announced that it is to build a MTO plant with a capacity of 300,000 tons/year of ethylene with start-up expected in 2013. PetroChina and the government of Shaanxi have announced a 1 Mton/year ethylene plant in Ya'an [33]. Next to the announced projects, Shaanxi has ethylene plants but records on the amount and size could not been obtained.

2.3.6. Refineries

Refineries have considerable CO_2 emissions; the majority are in low-concentration flue gas or process steams, which are not suitable for early-opportunity CCUS. The only emissions that possibly are suitable for CCUS originate from hydrogen manufacturing, amounting to 5–20% of the refinery emissions. Hydrogen is manufactured by reforming of natural gas or by coal gasification. Traditionally the CO_2 was removed from the resulting flue gas stream by chemical absorption, providing a high-purity CO_2 stream suitable for CCUS. However, in the past decades there has been a tendency to use PSA instead, which has lower operational cost and produces a very high-purity hydrogen stream, but produces a far less pure CO_2 stream. This stream contains a considerable amount of combustibles, with a considerable heating value, which makes incompatible with using this for CCUS. The feasibility of CCUS at refineries has to be assessed on a case-by-case basis.

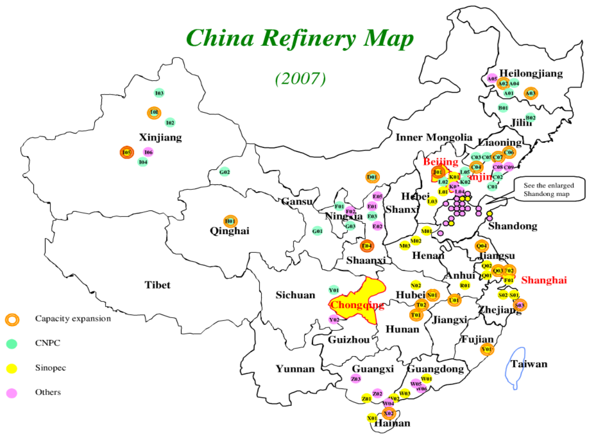

Figure 2.6: Geographical distribution of Chinese refineries [2]

Chinese refineries are dominated by a small number of companies, with CNPC and Sinopec being by far the largest. The past years have seen increasing foreign involvement. Refinery capacity has grown quickly, 270 Mtons/day in 2005 to 342 Mtons/day in 2008 and a projected 440 Mtons/day in 2011 [35].

Shaanxi Province is home to five refineries, as shown in Figure 2.6. The Yulin refinery, operated by Yanchang petroleum, will increase its capacity to three billion tons/year under the Eleventh Five-Year plan. There are no data on what type of technology is used for hydrogen manufacturing in the Shaanxi refineries, making it difficult to assess the suitability for CCUS.

According to the classification criteria for CO_2 emissions sources of different concentration and the actual concentration of CO_2 emission sources in various industries, it can be seen that: emissions sources of high CO_2 concentration are from chemical plants producing methanol, ethanol, dimethylether, ethylene oxide, ammonia, hydrogen; emissions sources of moderate CO_2 concentration are from cement plant, steel mills, etc.; while emissions sources of low CO_2 concentration are for the thermal power, ethylene plant, refining plant and other enterprises.

2.3.7. Methanol, ethanol and dimethylether production

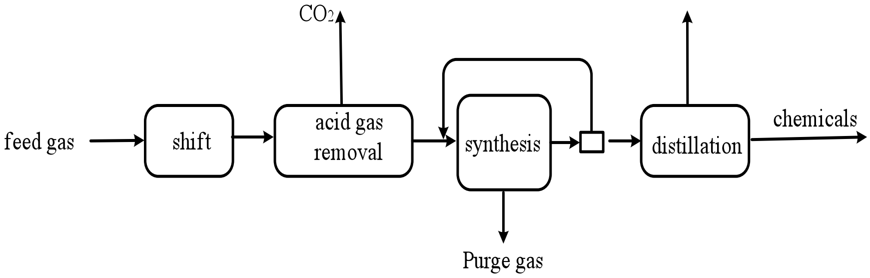

Figure 2.7. Process for methanol, ethanol and dimethylether production

Methanol, ethanol, dimethylether are all important intermediates of chemical raw materials, while methanol and dimethylether can also be main alternatives to liquid fuels. A schematic of the traditional system of methanol/ethanol/dimethylether production is shown in Figure 2.7. Generally speaking, the CO/ H_2 (molar ratio of CO to H_2) in the feed gas cannot meet the CO/H_2 (molar ratio) requirements for chemical products' synthesis before entering the Chemical Synthesis Unit. The water gas shift reaction are needed to make the H_2/CO (molar ratio of CO to H_2) in the feed gas meet chemical equivalent ratio requirements. In order to prevent the catalyst for chemical synthesis reaction from poisoning, the raw gas needs treatment by an acid gas purification unit for removal of sulphide, as well as to prevent the large amount of CO_2 as inert gas adversely affecting the chemical synthesis process, and usually CO_2 will be removed in this acid gas purification unit. After transformation and the acid gas removal, the fresh gas flow into the methanol synthesis and distillation unit, thus producing chemical products. CO_2 concentration in the traditional chemical production processes is often as high as 99% and above, while the impurities are relatively low, it is therefore very suitable for the EOR and geological storage.

2.3.8. Ethylene epoxide production

Ethylene oxide is a chemical intermediate of organic ethylene derivatives, which can undergo ring-opening reactions easily with water, alcohols, ammonia, amines, phenols, hydrogen halide, acid and merchantman. A large number of chemical products from these reactions can be applied in the production of intermediates and fine chemical products, which become indispensable chemical raw materials in a range of industrial products all over the world.

At present, the most widely used method to produce ethylene oxide is by oxidising ethylene in pure oxygen – ethylene (C_2H_4) and oxygen react to generate ethylene oxide (C_2H_4O). During the ethylene oxide production process, a fraction of the ethylene will be oxidised to CO_2 and H_2O. Since there is no other gas for dilution, CO_2 concentration is very high in the gas emitted from the ethylene oxide production process, that is, close to 100%. 0.46 tons of CO_2 will be produced for each ton of ethylene oxide.

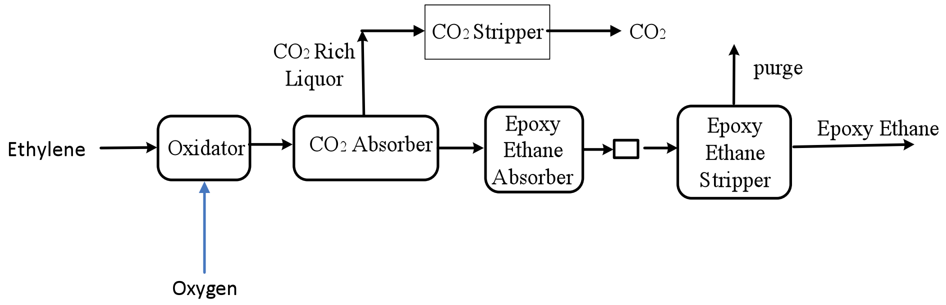

Figure 2.8: Process of producing ethylene oxide by oxidizing ethylene in pure oxygen

2.3.9. Hydrogen production process

Hydrogen for use as a raw material for clean and efficient energy and oil production has been paid increasing attention. The traditional methods of hydrogen production are mainly methane reforming, water electrolysis, coal gasification, partial oxidation of heavy oil and using methanol to produce hydrogen.

The reaction for hydrogen production by methane reforming is:

$$CH_4 + H_2O = CO + 3H_2 \qquad (1)$$

CO, formed from the process above reacts with water vapour (shift reaction between water and gas),to produce more hydrogen. The reaction is as follows:

$$CO + H_2O = H_2 + CO_2 \qquad (2)$$

The gas produced by the shift reaction needs the removal of CO_2, and then we can get the pure H2.

The main reactions for producing H2 by partial oxidation of methane are:

$$CH_4 + 0.5O_2 = 2H_2 + CO \qquad (3)$$

$$CO+H_2O= CO_2+H_2 \qquad (4)$$

In this process, CO and H_2 will be formed after a partial oxidation reaction between methane and oxygen, and CO will go further into the shift reaction with water gas to produce CO_2 and H_2. After CO_2 removal, pure H2 is obtained.

Hydrogen production by gasification consists of three main processes: gasification (reaction 5), the water gas shift reaction (reaction 6), and hydrogen's purification and compression. The reaction is as follows:

$$C+ H_2O= CO+ H_2 \qquad (5)$$

$$CO+ H_2O= CO_2+ H_2 \qquad (6)$$

In this process, coal is gasified into CO and H_2. Then, CO reacts with H_2O to produce CO_2 and H_2. Finally, pure H_2 is obtained after removal of CO_2.

The hydrogen production process requires CO_2 to be isolated individually, so CO_2 emissions concentration is high, almost free of any impurities and close to 100%. It is estimated that for every ton of hydrogen produced, CO_2 emissions are about 6.5 tons.

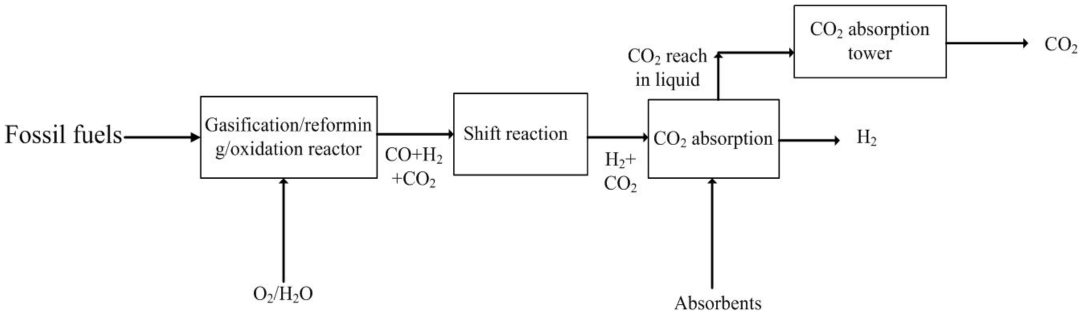

Figure 2.9: Hydrogen production process.

2.3.10. Calcium carbide production process

CaC_2 is commonly known as calcium carbide. The industrial product is grey, brown or black, and purple with high proportion of calcium carbide. The newly created section is shiny, grey, and absorbs water in the air. It can conduct electricity and the higher the purity, the better conductivity. The addition of water to CaC_2 will cause reaction to produce acetylene and calcium hydroxide. Reaction with nitrogen will yield calcium cyanamide.

Calcium carbide is one of the basic raw materials for the synthetic organic chemical industry, and is the key chemical raw materials for acetylene. Using calcium carbide to produce acetylene is widely used in metal welding and cutting.

Production methods are the aerobic thermal method and electric thermal method. The electric thermal method is used to produce calcium carbide and uses quicklime and carbon-containing raw materials (coke, anthracite or petroleum coke) in the calcium carbide furnace, to generate under the electronic arc of high temperature a melting reaction. The production process is shown in Figure 2.10. The main production process is: the mixture of feed materials at the top of the electric furnace top entrance or a pipe is fed into the furnace, then in the open or closed electric furnace it is heated to about 2,000°C calcium carbide is generated according to the following formula reaction:

$$CaO + 3\,C \rightarrow CaC_2 + CO \qquad (7).$$

Molten calcium carbide is removed from the bottom and, after cooling and then crushing, a finished product is packaged. Carbon monoxide generated in the reaction is discharged in different ways according to the type of calcium carbide furnace: in an open furnace, carbon monoxide burns on the material surface and combustion continues as the dust scatters outside the furnace; in the semi-closed furnace, part of the carbon monoxide is drawn out from a suction hood on the furnace and the remaining part is still on the material surface; in a sealed furnace, all the carbon monoxide is drawn out.

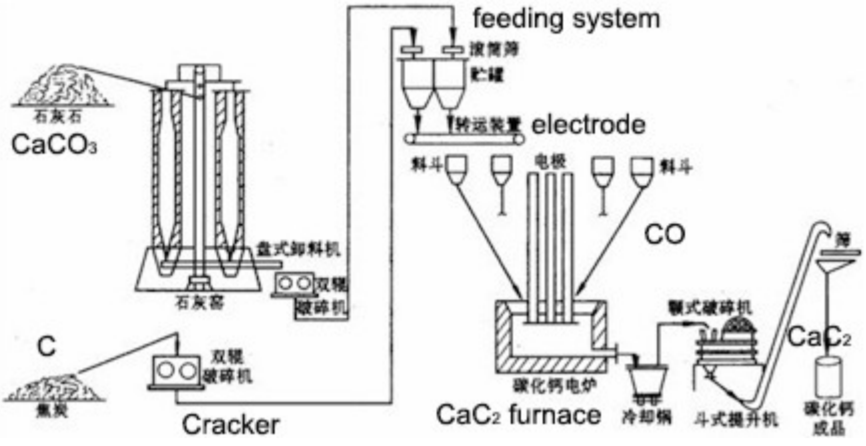

Figure 2.10: Calcium carbide engineering process flow diagram

Using the sealed furnace, the exhaust gas composition is: CO 75–90%; H_2 10%; CH_4 2–4%; CO_2 2–5%; and O_2 0.2–0.6%; N_2 1–2%. Therefore, in terms of exhaust emissions from the calcium carbide production process, the subsequent processing is needed (such as water coal gas conversion) to get a higher concentration of CO_2; the subsequent processing is not complicated, but relatively simple.

2.3.11. Cement production process

Cement is a building material with good performance. Cement is made of cement clinker via calcination. The cement clinker is mainly composed of the powdery raw materials, such as limestone, clay and iron by certain percentages. Raw materials are under continuous heating within the furnace to make it through a series of physical and chemical changes to become clinker. The cement manufacturing process can be divided into the following phases: exploitation of raw materials, raw material preparation, clinker calcination, milling, and shipping.

CO_2 is produced from the clinker calcinations phase. The clinker is heated in cement kilns. There are two main categories of cement kiln. One is positioned horizontally but with a slight slope and it can be operated with rotary movement, also known as the rotary kiln; the other is in the vertical position with rotation, known as the shaft kiln. At present, most production of cement is done with the rotary kiln, but the proportion of shaft kiln usage is also very big in China.

CO_2 produced during cement production comes mainly from two processes: the decomposition of the raw materials such as limestone and the fuel combustion. Limestone and other raw materials and fuels (such as coal, etc.) go into the rotary kiln, air is provided, then fuel combustion releases considerable heat. The limestone and other raw materials absorbing heat will be calcined into CaO and CO_2. The offgas gathered from the rotary kiln contains about 25% CO_2 after heat recovery, dust removal and other measures. CO_2 emissions from cement production are somewhat different, depending on the way of the raw materials are fed. Generally speaking, the CO_2 emissions are 0.87–1.11 t CO_2 / t cement.

2.3.12. Steel production

In general, the steel plant CO_2 emissions are from the coking process, the blast furnace iron making process, the furnace and Basic Oxygen Furnace (BOF) iron making process. The coking process is the process of making coal into coke. CO_2 emission in the process is from the coke oven gas (coal volatile releasing) combustion. Part of the coke oven gas produced by the coking process is combusted to produce a high-temperature flue gas in order to meet the energy needs of the coking process itself. The rest of the gas is either burned and is emitted or is recycled. Coke oven gas is mainly a hydrogen-rich gas; the CO_2 concentration is low – usually less than 10%. CO concentration is also low and usually less than 15%.

The blast furnace iron making process is another source of CO_2 emissions. In the blast furnace iron making process, the coke will generate CO_2 gas when it reacts with oxygen in the air and iron ore. Blast furnace gas contains about 20–25% CO_2. Large-scale steel mills generally recycle blast furnace gas, and in the small steel plant, blast furnace gas will be emitted after combustion.

CO_2 emissions in the billet heating process are from the combustion of the fuel. The heat used for billet heating is recovered from coke oven gas, blast furnace gas and other supplementary fuel burning. Therefore, the CO_2 concentration in billet heating process emissions is not high, generally less than 15%.

A converter is one of the main pieces of steelmaking equipment. To get the right carbon proportion in the steel that meets the product requirements, a small amount of carbon in the molten iron and oxygen (provided by the oxygen lance) is reacted in the converter to generate CO_2. But this portion of the gas is difficult to recycle. Overall, to make a ton of iron and steel, the CO_2 emissions are about 1.3 tons.

2.4. Summary

According to the classification criteria for CO_2 emissions sources of different concentration and the actual concentration of CO_2 emission sources from various industries, it can be seen that: emissions sources of high CO_2 concentration are from chemical plants producing methanol, ethanol, dimethylether, ethylene oxide, ammonia, hydrogen; emissions sources of moderate CO_2 concentration are from cement plant, steel mills, etc.; while emissions sources of low CO_2 concentration are for the thermal power, ethylene plant, refining plant and other enterprises.

From this analysis, the factors and scales of CO_2 emissions for different industrial processes are different. CO_2 emission factors of typical industrial processes is shown in Table 2.7 [36].

Table 2.7: CO_2 emission factors in different industries.

	Cement			Power sector		
	Dry-clinker based	Dry-cement based	Wet-clinker based	Coal-fired	Oil-fired	Gas-fired
Emission factor	0.882 Mg/t	0.867 Mg/t	1.111 Mg/t	1.0 kg/kWh	0.5 kg/kWh	0.4 kg/kWh

	Oil refinery	Epoxy ethane	Ammonia
Emission factor	0.219 Mg/t	2.541 Mg/t	3.800 Mg/t

	Ethylene	Hydrogen production	Steel
Emission factor	0.458 Mg/t	6.15 Mg/t	1.27 Mg/t

3. High-purity CO_2 sources in Shaanxi Province

3.1 General description of CO_2 emissions in Shaanxi Province

Shaanxi Province has abundant coal resources. This western province is less developed but rich in energy resources and its energy structure is dominated by coal. The chemical industry is still one of the most important industries to promote economic growth.

Although the energy saving and emission reduction task is accomplished during ‘Eleventh Five-Year’ period (2006-2010), the output values of six energy-intensive industries, which are power, chemical, petrochemical, nonferrous metals, metallurgy and building materials, industries’ account for more than half of whole industrial outputs in Shaanxi. Pollution and GHG reduction in these industries has become increasingly important, but the conflict is that the fundamental change to this kind of industry structure is difficult in the short term.

Shaanxi Province's carbon dioxide emissions are mainly derived from fossil fuel consumption. In 2005, total emissions of CO_2 of Shaanxi Province’s were about 138 million tons, accounting for 2.4% of the national emissions. The main CO_2 emissions of Shaanxi Province are from its power plants, accounting for about 70% of the total emissions, followed by the cement, ethylene and synthetic ammonia industries, each accounting for about 10%. Hydrogen production CO_2 emissions account for about 0.7%.

According to preliminary estimates, Shaanxi carbon dioxide emissions from the use of fossil fuels increased from 138 million tons in 2005 to 209 million tons in 2009 and it will soar to 450 million tons in 2015. Because the energy consumption of coal in the chemical industry will still be high, CO_2 emissions in Shaanxi will become more prominent with the development of large coal chemical projects in the next few years. In 2015, carbon dioxide emissions are expected to reach 180 million tons only from coal use in the chemical industry.

Since 2011, carbon emission reduction has been listed as the binding target for energy saving. Shaanxi's national economic and social development outline for the Twelfth Five-Year guidelines, proposes that the amount of energy consumption will decrease substantially and carbon dioxide emissions will be decreased by 15%. Shaanxi will be a national low-carbon demonstration province. Low carbon development, low carbon economy and low carbon life is expected to be the main theme of Shaanxi's economic development and social life during the Twelfth Five-Years guideline period.

3.3. Classification of industrial sources according to CO_2 emissions

The capture of CO_2 is an important part in the whole CCS project. It is estimated that the capture cost accounts for 70% to 80% of the whole CCS chain cost. The classification of the CO_2 industrial sources according to some certain principles is beneficial to the search for CO_2 sources suitable for early CCS demonstration that have a low capture costs.

It is well known that the cost, energy consumption/penalty and the scale of a CO_2 demonstration project influence its effectiveness. Industrial enterprises will be confident in CCS if the capture cost and energy penalty of the demonstration project are low and acceptable. The application of this type of low cost project can play the important role and improve the development of CCS technologies. Meanwhile, good economic performance and low energy penalties will bring more policy support for CCS. On the contrary, if the demonstration project has bad economic performance and a high energy penalty, it will have a negative impression, which will make it more difficult to develop and get support from policy makers.

The scale and purity of the CO_2 sources, impurity levels and the difficulty of the pre-treatment methods determine the cost and energy penalty of CO_2 capture in the demonstration project. As analysed in this report, low purity CO_2 sources will lead to high-energy penalty and capture costs. It is easy to understand that high impurity content will result in complex technology, high cost and high-energy penalty in the separation process. If the sulphur content of the CO_2 source is high, a desulphurisation process is necessary to prevent corrosion. Free water in the flue should also be removed before transportation. Otherwise, corrosion will be accelerated in the presence of acidic components and free water. Because of the scale effect, large scales will result in small specific investments and then low capture costs of CO_2. Meanwhile, the scale of CO_2 sources will influence the effectiveness of a CCS demonstration project. If CCS can be demonstrated, the scale of CCS should not be very small. The power industry in particular will experience the CO_2 emission rates of a conventional power plant reach 400t/hr. If the scale of CO_2 capture is too small, no obvious demonstration effects will be achieved. Furthermore, the scale of CO_2 source should match with the sink in terms of the amount of CO_2.

Thus, in this report, we set a series of criteria to classify the industrial CO_2 sources aiming at selecting sources suitable for a CCS demonstration.

1) The CO_2 emission scale
2) The CO_2 purity
3) The impurities
4) The ownership of the CO_2 sources

Table 3.1 The classification of C CO_2 sources.

	Plant type of CO2 source	CO_2 purity	Purity class	Emission scale, Mt/y	Desulphurisation or not	Dehydration or not	Difficulty level of pre-treatment
Power plant	Coal fired	13%~15%	Low	7.5~60	Yes	Yes	Hard
	Oil fired	12%~18%	Low	3.75~30	Yes	Yes	Hard
	Gas fired	3%~8%	Low	3~24		Yes	Hard
Ethanol/ Methanol/ Dimethyl ether plant		99%	High	0.25~2.5	No	No	Easy
Iron and Steel Plant		15%-25%	Low-medium	2 ~10	Yes	Yes	Hard
Cement building materials factory	Cement plant	20%-25%	Low	0.1~2	Yes	Yes	Hard
Refining	Refinery plant	8%	Low	0.1~0.6	Yes	Yes	Hard

chemical plant		8%	Low				Hard
	Ethylene plant	12%	Low	0.25~2.5	No	No	Hard
	Ethylene oxide plant	100%	High	0.2~1	Yes	No	Easy
	Hydrogen plant	99%	High	0.2~0.6	No	No	Easy
Chemical Fertiliser Plant	Ammonia synthesis plant	100%	High	0.38~3.8	No	No	Easy

3.4. Identification of the main sources of high purity CO_2 emissions in Shaanxi province

High purity CO_2 sources are mainly in the chemical industries, especially the coal chemical industries. Coal is the most important energy resource of China, because it is not only a fuel, but also chemical material. In recent years, the international oil price has been varying dramatically, leading to the increasing demand for alternative chemical materials and alternative energy sources. Clean coal utilisation has been one of the top emerging energy industries. The future coal chemical industry will be a major concern with so many listed companies' intervention in this field.

The outputs of main coal chemical products have been growing continuously and rapidly in recent years. Methanol production of China was 11.3 million tons in 2009, and 8.1 million tons in the first half of this year, with a year-on-year growth rate of 53.3%. The synthetic ammonia production of China was 51.4 million tons in 2009, and 26.5 million tons in the first half of this year, with a year-on-year growth rate of 4.6%. Furthermore, there are a large number of projects under construction or extension and coal chemical industry projects under plan.

The new emerging coal chemical industries, which use clean coal gasification technologies as the leading operation, have influenced the development of coal chemical industries due to the advantages of high energy efficiency, full utilisation of resources and low greenhouse gas emissions. According to experts' estimates, the energy consumption per unit of the emerging coal chemical products is more than 20% lower than the conventional coal chemical products.

In Shaanxi Province, high purity CO_2 sources mainly include methanol plants, dimethyl ether plants, hydrogen plants, ammonia synthesis plants and calcium carbide plants. As a province abundant in resources and energy sources, coal chemical industries are important parts of its industry structure.

Northern Shaanxi region is a rare mineral-rich area of the world, abundant in coal, oil, natural gas and rock salt. The proven coal reserves ranks third in China and the remaining recoverable coal reserves are estimated at 16.85 million tons, 14.46 million tons of which is suitable for coal chemical industry. Most of the coal is of high quality and a suitable raw material for the power and chemical industries with low dust, low sulphur, low phosphorus and high calorific value. Therefore, Northern Shaanxi region is considered as one of the energy continuous places and energy chemical industry bases.

Shaanxi Province lies in Central China, which has advantages in terms of location. At the same time, it has many research institutes where a large number of technical personnel skilled in manufacture and management have been cultivated. Many advanced technologies are mastered, such as the leading domestic coal liquefaction technology. The world's first ten thousand ton DMTO (dimethyl ether/methanol-to-olefin) system was recently successfully experimentally tested in Shaanxi, which was identified as the international leading technology in the national science and technology achievements appraisal. Several Top 500 global corporations and domestic famous enterprises including Shenhua and Changqing Oilfield companies have been attracted and settled in Shaanxi. A group of projects have started successively or been actively prepared, such as a coal-electricity integrated complex, coal-to-methanol, methanol-to-olefin, acetic acid, coal liquefaction and coal-salt chemical industries.

From the planning and the current state of development, we can see that the development prospect of the coal chemical industries is promising in Shaanxi. However, the development of coal chemical industries is limited by local resources and environmental protection, such as the protection of water resources. The coal reserves are concentrated in the Northern Shaanxi region, especially Yulin, which is an arid area. The water demand in the coal chemical industries is huge. It was estimated that when the planned projects were completed in 2010, the local water resource load capacity would reach saturation. The government has been attaching importance to the protection of water and other environmental resources, and has taken some appropriate actions. A reasonable integrated plan and a series of measures for environmental protection can promote the development of the coal chemical industries in Shaanxi.

The number of main methanol plants in Shaanxi is listed in Appendix I. Most of these plants are located in Yulin region. The accumulative total methanol productions are 8.5 mega tons, and accumulative total CO_2 emissions are 14.4 mega tons. Relying on abundant coal and natural gas resources, Shaanxi became one of the heavy chemical industry bases of China. The methanol industry has become one of the prioritised industries in Shaanxi and its production scale has been growing rapidly in recent years, because methanol is an important chemical product. There are many methanol projects in planning or under construction, such as Shenmu Chemical Industry Co. Ltd. and Yulin energy and chemical plants. As an ideal alternative fuel, there is a highly promising future for the methanol industry with the development of alternative fuel technology. Dimethyl ether is another important type of chemical material and promising alternative liquid fuel, and the dimethyl ether industry is supported by Shaanxi Province as one development direction of the coal chemical industry. The number of main dimethyl ether plants in Shaanxi is listed in Appendix III. Most of these plants are located in Yulin region as well. The accumulative total dimethyl ether productions are 2.9 mega tons, and accumulative total CO_2 emissions are 7.3 mega tons.

Hydrogen production technology is a key development direction of clean energy, especially for provinces abundant in coal, such as Shaanxi. The hydrogen industry in Shaanxi is at an early stage, and there is only one hydrogen plant in the region, but there will be a bright future for hydrogen production from coal with an increasing requirement for environmental protection. The only hydrogen plant in Shaanxi (Appendix IV) is located in Yulin region. The accumulative total hydrogen production is 90000 Nm^3/h, and accumulative total CO_2 emissions are 0.44 mega tons. The ammonia synthesis industry is one of the traditional coal chemical industries in Shaanxi. The annual total production scale is more than 50 million tons, and has been increasing rapidly in recent years. The number of main ammonia synthesis plants in Shaanxi is around 14 (Appendix V), distributing in all regions of Shaanxi. The accumulative main synthesis ammonia productions are 5.2 mega tons, and accumulative total CO_2 emissions are 19.5 mega tons. As an important raw material for acetylene production, calcium carbide production has a significant scale. The number of main calcium carbide plants in Shaanxi is around 21 (Appendix IV). The accumulative total calcium carbide production is around 0.42 mega tons, and the accumulative CO_2 emissions are also large.

3.4. Detailed description of the main sources of high purity CO_2 emissions in Shaanxi Province.

The above discussion has identified several potential CO_2 sources in or near Shaanxi Province that may be suitable for CCUS against very low costs. These sources are in the CTL, ammonia, biomass conversion and ethylene production sectors.

According to the survey of CO_2 sources in non-power industries of Shaanxi, this section will give a detailed introduction of some typical and representative high purity CO_2 sources, including emission scale, purity, factory type and so on, to provide some references for the selection of CO_2 sources in the CCUS demonstration project.

3.4.1. Ammonia synthesis plants

Shaanxi Heimao Coaking Stock. Co. Ltd.: located in Hancheng City, is a recycling economy enterprise involving sectors of coke, power generation, chemical industry and construction material. The company set up six projects, one of which is a co-production of ammonia with methanol project with an output of 100,000 t/y (this project belongs to its subsidiary company Heimao Energy Utilization Co. Ltd.). Its synthesis of ammonia production is about 90,000 t/y, and the by-product methanol production is about 10,000 t/y. About 380,000 tons of CO_2 with the purity of 99% is generated in this plant every year.

Shaanxi Qinling Fertilizer Company: located in Baoji city, has synthesis ammonia production capacity of 160,000 t/y. About 600,000 t/y of CO_2 with a purity of 99% is generated in this plant.

Shaanxi Weihe Coal Chemical Industry Group Co. Ltd.: located in Weinan city, has the synthesis ammonia production of 300,000 t/y and the urea production of 520,000 t/y with bituminous coal as a raw material. About 1,140,000 t/y of CO_2 with a purity of 99% is generated in this plant.

Shaanxi Chenghua Co. Ltd.: located in Chenggu county, Hanzhong city, is the only enterprise which has urea production and waste heat driven power generation projects in Southern Shaanxi Province. It has synthesis ammonia production of 120,000 t/y, urea production of 140,000 t/y and ammonium bicarbonate production of 60,000 t/y. About 450,000 t/y of CO_2 with a purity of 99% is generated in this plant.

Shaanxi Coal and Chemcial Industry Group Co. Ltd.: located in the fine chemical park of Hua county, Weinan city, has synthesis ammonia output of 260,000 t/y, the urea output of 320,000 t/y, the ammonium phosphate output of 260,000 t/y and the three elements compound fertiliser output of 100,000 t/y. In addition, the technical improvement project for energy conservation and emission reduction contracted by Shaanxi Coal and Chemical Industry Group Co. Ltd. has started total construction in October 2008, and was put into operation in November, 2011. This project has synthesis ammonia output of 300,000 t/y and urea output of 940,000 t/y. About 2,280,000 t/y of CO_2 with a purity of 99% is generated in this plant.

Yanchang Petroleum Xinghua Large Chemical Industry Project: owned by Shaanxi Yanchang Petroleum (Group) Co. Ltd. and located in Xingping City, was put into operation on 28 December 2011. It includes synthesis ammonia output of 300,000 t/y, methanol output of 300,000 t/y, soda output of 300,000 t/y and ammonium chloride output of 324,000 t/y. This is an integrated system with ammonia, alcohol and alkali outputs. In the system, the waste gases of CO and CO_2 in the ammonia synthesis process can be used for methanol synthesis, and the purge gas in the methanol synthesis process can be used for ammonia synthesis. This can reduce the greenhouse gas emissions and there are no sulphurous pollutants discharged in the process. About 1,140,000 t/y of CO_2 with a purity of 99% is generated in this plant.

Shaanxi Fangyuan Chemical Industry (Group) Co., Ltd.: located in Yuyang district, Yulin City, operates a synthetic ammonia production line by adopting the water coal slurry gasification technology, KELLOGG natural gas steam conversion technology and residual vaporisation technology. Synthetic ammonia output is 300,000 t/y, among which 180,000 t/y is used for urea production and the remaining 120,000 t/y together with the by-product are used for soda production. About 1,140,000 t/y of CO_2 with a purity of 99% is generated at this plant.

3.4.2. Methanol plants

The **1,800,000 t/y methanol project in Huangling County, Yan'an City** has been approved and will be co-constructed by the People's Government of Yanan city, Shaanxi Yanchang Petroleum (Group) Co. Ltd. and the Hong Kong and China Gas Company Ltd. This project is expected to be constructed in 2013. With coal, gas and oil as raw materials, this project has a methanol output of 1,800,000 t/y, MTO (methanol-to-olefin) output of 600,000 t/y, light oil reforming capacity of 400,000 t/y, polyethylene output of 450,000 t/y, polypropylene output of 250,000 t/y, butanol-octanol output of 200,000 t/y, and ethylene propylene rubber output of 60,000 t/y. About 4,500,000 t/y of CO_2 with a purity of 99% is generated in this plant.

The **1,800,000 t/y methanol production and deep processing project in Fu County, Yan'an City,** was constructed and is operated by Yanchang Petroleum Yan'an Energy Chemical Industry Co. Ltd., which is one of the subsidiary enterprises of Shaanxi Yanchang Petroleum (Group) Co. Ltd. About 6,800,000 t/y of CO_2 with a purity of 99% is generated in this plant.

The **1,800,000 t/y coal to methanol project in Jingbian County, Yan'an City** is in the charge of Shaanxi Yanchang China Coal Yulin Energy Chemical Industry Co. Ltd., a large scale chemical enterprise making comprehensive utilisation of coal, gas, oil and salt, which was jointly established by Shaanxi Yanchang Petroleum (Group) Co. Ltd. and China National Coal Group Co. Ltd. It is responsible for the construction of the start-up projects in the Jingbian industrial zone of the comprehensive utilisation of energy engineering and chemical industries, which is 10 km away from the northeast of Jingbian County. This industrial zone has total methanol output of 1,800,000 t/y. This project is planned to start in 2014, and the expected CO_2 emission is 6,800,000 t/y with 99% purity.

The **1,700,000 t/y methanol project in Yuheng industrial zone of Yulin City** is undertaken by Shaanxi Yanchang Petroleum Yulin Coal Chemical Company, a wholly owned subsidiary of Shaanxi Yanchang Petroleum (Group) Co. Ltd. The company owned the acetic acid project with output of 1,000,000 t/y and is the key project of its kind in Shaanxi. The first stage project has methanol output of 200,000 t/y and acetic acid output of 200,000 t/y. The second stage has methanol output of 1,500,000 t/y, acetic acid output of 400,000 t/y, vinyl acetate output of 300,000 t/y, acetic anhydride output of 200,000 t/y and acetate fibre output of 100,000 t/y. The CO_2 emissions are expected to be 6,400,000 t/y with purity of 99%.

The **600,000 t/y methanol project in Weicheng County, Xianyang City** is undertaken by Shaanxi Xianyang Chemical Industry Co. Ltd., a wholly owned subsidiary of Shaanxi Investment Group Co. Ltd. It has a coal to methanol output of 600,000 t/y and a power generation capability of 25 MW. The CO_2 emissions are about 5,700,000 t/y.

The **gas to methanol/dimethyl ether project in Yanchang County, Yan'an City** belongs to Shaanxi Yanchang Petroleum (Group) Co. Ltd. and the People's Government of Yan'an City. The methanol output of the first stage is 600,000 t/y. The second stage is designed to produce dimethyl ether directly from syngas, with the output of 700,000 t/y and is in the phase of inviting investment. The CO_2 emissions are expected to be 3,250,000 t/y after the project is established.

The **coal to methanol project of Shaanxi Shenmu Chemical Industry Co.** is located in the industrial development zone of Shenmu County, Yulin City. The designed methanol output is 600,000 t/y. The first stage with output of 200,000 t/y has already been put into production. The CO_2 emissions are expected to be 1,500,000 t/y.

The **coal to methanol project of Yanzhou Coal Yulin Energy Chemical Industry** is located in the Caojiatan Town, Yuyang County, Shaanxi Province. The designed methanol output is 2,300,000 t/y, and the present output is 600,000 t/y during the first stage. The CO_2 emissions are 7,250,000 t/y.

The **coal to methanol project in the economic development zone of Yulin City** has a methanol output of 600,000 t/y and the CO_2 emissions are 1,500,000 t/y.

The **methanol plant of Changqing Oilfield, located in Jingbian County, Yulin City** belongs to Changqing Branch of China National Petroleum Corporation. The methanol output is about 100,000 t/y. The CO_2 emissions are about 250,000 t/y with purity of 99%.

3.4.3. Hydrogen plant

The **90,000 Nm^3/h hydrogen project of Shaanxi Shenmutianyuan Chemical Industry Co. Ltd., located in Shenmu County, Yulin City**, produces hydrogen from coal. The CO_2 emissions are about 400,000 t/y with purity of 99% [38].

3.4.4. Ethanol plant

Shaanxi Baoji Alcohol Plant, located in Baoji City, is a large scale light industry enterprise which produces 350,000 tons of beer and 30,000 tons of alcohol every year. Its main products include superior alcohol and edible alcohol with the brand of 'Tangqingchencang', and various types of beer with the brand of 'Baoji'. The CO_2 emission amount is about 30,000 t/y.

3.4.5. Dimethyl ether plants

The **1,000,000 t/y** dimethyl ether **project in Pucheng County was constructed by Shaanxi Coal and Chemical Industry Group Co. Ltd.** It adopts advanced pressurised gasification technology for coal-water slurry with coal as the raw material. The outputs of methanol and dimethyl ether are about 1,500,000 and 1,000,000 t/y, respectively. The expected annual CO_2 emissions are about 6,000,000 tons.

The **1,000,000 t/y dimethyl ether project in Xianyang City was in the charge of Shaanxi Carbonification Energy Co. Ltd.** The dimethyl ether outputs of the first and second stages are about 400,000 and 600,000 t/y, respectively. The construction will be completed in 2013. The expected CO_2 emissions amount is about 2,500,000 t/y.

The **1,000,000 t/y dimethyl ether project in Yulin City was in the charge of Shenfu economic development zone and is located in the Jinjie industrial park in Shenmu County**. The expected annual CO_2 emissions are about 2,500,000 tons.

Jointly, these sources add up to 62.5 Mt CO_2 until 2016.

3.5. Identification of the sources suitable for a demonstration project

3.5.1. Definition of criteria for selecting sources for a demonstration project

The characteristics of CO_2 sources directly affect the cost and energy penalty of CO_2 capture, and exert a great influence on the cost and energy penalty of the whole demonstration project. It is of key importance to select suitable CO_2 sources for the demonstration project. The most important factors that influence the demonstration project are the technical feasibility, cost and energy penalty, so the following two key principles must be taken into consideration when selecting CO_2 sources.

1. **Technical feasibility and maturity principle.** It means that the capture technology is achievable in engineering, and the mature technology should be given priority to reduce the risk and uncertainty of the project.

2. **The energy penalty and cost minimisation principle.** To get an effective demonstration, it is necessary to minimise the cost budget and energy penalty of CCS. For the EOR technology, the benefits brought by the increase of oil exploitation should not be less than the cost of capture and transportation. According to the survey from petroleum enterprise including PetroChina, the acceptable price of CO_2 for petroleum enterprise is 20$/t, so these enterprises can only make balance or profit when the cost of capture and transportation is less than 20$/t.

The following points are important in the energy penalty and cost minimisation principle:

- Whether the scale of source can meet the project requirement should be considered first when selecting CO_2 sources for demonstration projects. If the scale is too small, it is difficult to achieve the required demonstration effect and the unit cost and energy penalty will be too high for the CO_2 capture and transportation because of the scale effect (the larger the scale, the lower the unit cost). Using the pipeline transportation as an example, the minimum economical transportation amount is 1.8 Mt/y, so it is unlikely to take a small scale CO_2 source as the single source in the demonstration project.

- Secondly, it is better to select sources with CO_2 purity higher than 95% for the reduction of the energy penalty and the cost of the demonstration project. The sulphur and water contents are relatively low in the emission gas with high CO_2 purity. Generally, in case of serious corrosion, the composition requirements for pipeline transportation are listed as follows: without free water, water vapour content less than $4.8\times10^{-4}/m^3$， H_2S content less than 1500 ppm (mass fraction), O_2 content less than 10 ppm (mass fraction). For EOR sequestration, the N_2 content should be lower than 4% (mole fraction), and the requirement for water vapour and O_2 contents are also high. It is better to use the CO_2 sources that can meet the requirement for transportation and sequestration without pre-treatment, so the procedures can be simplified and total energy penalty and cost can be reduced.
- Thirdly, the geographical location and surrounding transportation of CO_2 sources should also be taken into account. If the distance between the source and the storage site is longer than the economical distance (150 km for pipeline transportation), or the transportation is in a difficult region (e.g. in mountainous terrain which is not suitable for pipe laying), it is unlikely to be selected as the CO_2 source for a demonstration project. The ownership of CO_2 sources (government, state-owned enterprise or private enterprise) is another consideration. The responsibility of the whole chain of a CCS demonstration project is shared by different industries and organisations, so a clear understanding of the ownership of the source and storage site helps to understand the difficulty level of the operation and the coordination of the demonstration project. In addition, a key factor is whether or not the local government supports the sale of CO_2 to a CCS demonstration project.

The criteria for selecting CO_2 sources of demonstration formulated according to the minimisation of energy penalty and cost are listed in Table 3.2..

Table 3.2: Criteria for selecting sources of demonstration.

1.	The CO_2 emission meets the scale requirement of demonstration project, and reaches the economical transportation amount. For the pipeline transportation, the amount should be no smaller than 1.8 Mt/y.
2.	Selection of high purity CO_2 sources. The purity should be higher than 95%.
3.	The gas composition meets the requirements for transportation and sequestration, and no pre-treatment is required, such as desulphurisation and drying. In case of serious corrosion, the composition requirements for pipeline transportation are listed as follows: without free water, water vapour content less than 4.8×10-4/m^3， H_2S content less than 1500 ppm (mass fraction)， O_2 content less than 10ppm (mass fraction). And for EOR sequestration, the N_2 content should be lower than 4% (mole fraction), and the requirement for water vapour and O_2 contents are also high.
4.	Good transportation conditions around the CO_2 sources. For pipeline transportation, the recommended minimum economical distance is 150km. The CO_2 sources in mountainous area should not be selected.
5.	The ownership properties of CCS sources. Choose enterprises that can take charge of both CO_2 transportation and sequestration to coordinate the whole CCS chain.
6.	Local policies should support the sale of CO_2 to CCS demonstration projects.

3.5.2. List of sources suitable for a demonstration project

Based on the above criteria, the selected proper CO_2 sources for CCS demonstration project are shown in Table 3.3.

Table 3.3: CO_2 sources suitable for demonstration project.

No.	Plant Name	Location	Plant type	Emission scale	CO_2 purity	Policy support
1.	Yuheng industry zone	Yulin	Methanol	6400000t/y	High	YES
2.	Jingbian	Yanan	Methanol	6800000t/y	High	YES
3.	Huangling	Yanan	Methanol	4500000t/y	High	YES
4.	Yanchang	Yanan	Methanol/DME	3250000t/y	High	YES
5.	Shenmu	Yulin	Methanol	1500000t/y	High	YES
6.	Changqing	Yunlin	Methanol	250000t/y	High	YES
7.	Shenfu	Yulin	DME	2500000t/y	High	YES
8.	Fangyuan Yuyang	Yulin	Ammonia	1140000t/y	High	YES
9.	Yanchang Petroleum	Xingping	Ammonia	1140000t/y	High	YES

3.5.3. Map of the applicable sources in Shaanxi Province

Figure 3.1. The applicable CO_2 sources for CCS demonstration.

The proper CO_2 sources for CCS demonstration project in Shaanxi Province are shown in Figure 3.1. Most of these sources are methanol plants, dimethyl ether plants and ammonia synthesis plants – these have high purity CO_2, which means low cost and energy penalty for CO_2 capture and needs no pre-treatment before transportation. These sources are suitable for the early CCUS demonstration project. These emission sources are located intensively in heavy chemical industry bases, such as Yulin and Weinan. The Yulin area is abundant in coal and natural gas, and it is also one of the ideal CO_2 sequestration sites. CO_2-ECBM or CO_2-EOR can be demonstrated in these areas. There are also many high purity CO_2 sources in the Yan'an area, and some of these sources are owned by Yanchang Oilfield or Changqing Oilfield. So the CO_2 from sources can be used directly to enhance oil recovery rates.

4. Conclusion

As an integral part of the production process certain non-power industrial activities often have,high-purity off-gases of CO_2. The CO_2 emissions from coal and gas-fired power plants normally have a CO_2 concentration in the flue gas of between 8 to 15%, whereas certain industrial processes such as hydrogen, ammonia and methanol production can have CO_2 concentrations of between 50% to almost 100%. As the capture step of CCUS projects with low concentrated flue gases entail the highest cost both in terms of initial investment and operating costs (energy, capture solvent), industrial processes represent potentially interesting business cases. Furthermore, low cost 'early opportunity' CCUS projects within industry can result in technological learning and the development of best practice, which may contribute to reducing costs for projects in the power sector and other industries.

High-purity CO_2 streams are primarily found amongst activities in the oil and gas industry, base chemical production and oil refining industries. The processing of natural gas from the field to market specification involves the removal of CO_2 (which can be between 2% to 70% of the produced gas) in order to raise the combustibility. CO_2 is captured using conventional CO_2 scrubbing techniques, which results in a stream of CO_2 pure enough to be used directly in CCUS activities. Ammonia is produced through the gasification of coal or the reforming of natural gas, which result in a synthetic gas, of which the CO_2 content must removed. Where chemical adsorption capture technologies are used, this process also leads to a high-purity stream of CO_2. The removal of CO_2 is also required during the processes of hydrogen and methanol production, both based on the fundamental process of stream-methane reforming (SMR).

Although processes such as coal-to-liquid (CtL) production and biomass conversion (for either biofuel or synthetic natural gas production) are not currently prolific in China, these processes may become increasingly important given the increasing cost of fossil-based transport fuels. The Fischer-Tropsch process, which converts a syngas of carbon monoxide and hydrogen (derived either from coal or biomass gasification) into liquid hydrocarbons, requires that CO_2 is removed from the syngas prior to the commencement of the process. Therefore future industrial activities for the production of alternative transport fuels may also provide a source of high-purity CO_2 streams for CCUS projects.

The large deposits of high-quality coal in Shaanxi mean that a large industry based on the conversion of coal to high value chemical products can be sustained well into the future. This combination of factors also means that the province has significant sources of high-purity CO_2 to develop low-cost CCUS demonstration and commercial projects. As part of this study, a detailed site-by-site inventory of potential high-purity sources has been completed for the province in Section 3. The CO_2 emissions from industries with known high-purity sources in the Shaanxi Province can be found in Figure 4.1.

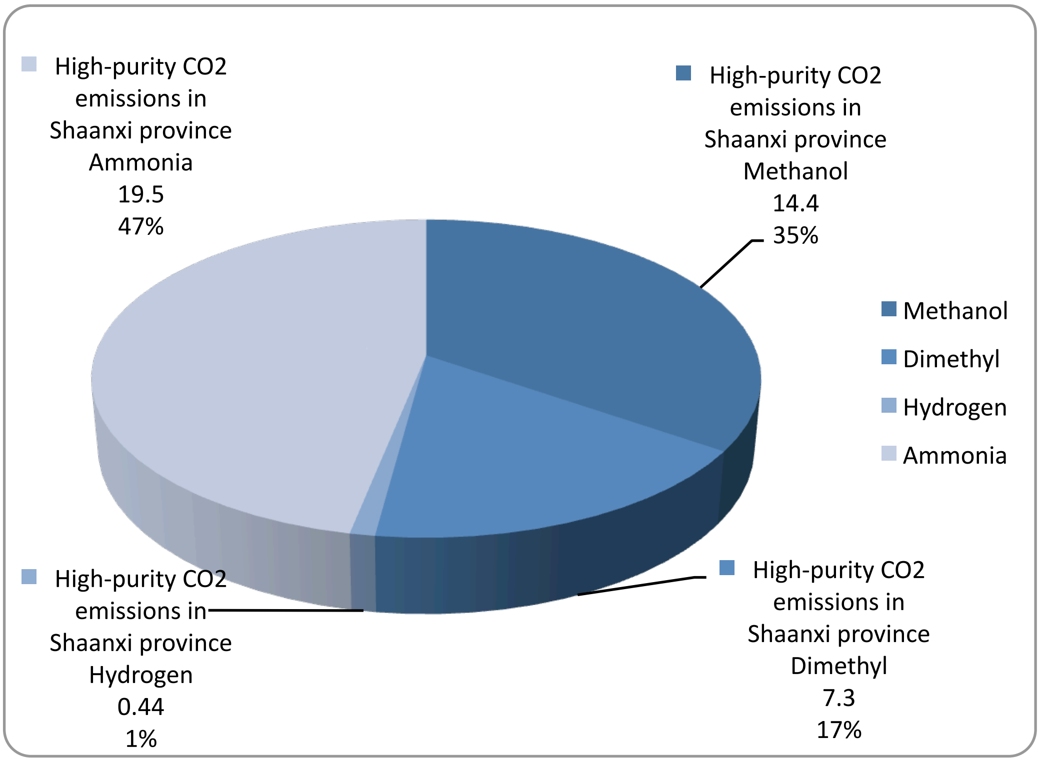

Figure 4.1: CO_2 emissions from industries with known high-purity sources in the Shaanxi Province

Although the CO_2 emissions are accumulated for each industrial activity, meaning that other non high-purity sources of CO_2 may be included in the data, Figure 4.1 provides an indicative picture of the technical potential for capturing CO_2 (much of which may be high-purity) from a range of industrial activities within the Shaanxi Province.

To identify specific opportunities for CCUS demonstration projects in the province, a set of selection criteria have been developed (see Table 3.2) which includes a minimum project size threshold of 1.8MtCO2/yr, a CO_2 purity limit of 95% and a maximum transportation distance to the point of injection of 150km. In addition to these limits, an evaluation of local policies, ownership issues and the suitability of the gas composition for enhanced oil recovery have been assessed. This selection procedure resulted in a list of nine potential demonstration projects involving methanol, ammonia and dimethyl production plants (Table 3.3). For further research, the authors recommend a site-by-site technical survey to assess potential technical barriers and to develop cost estimations in order to further refine the selection of identified CCUS demonstration projects from non-power industrial sources in Shaanxi Province.

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Appendices

Appendix Ⅰ: Methanol plant in Shaanxi

No.	Type	Name	Yield (ton/year)	CO_2 emission		Address	City	County	Website	Remark
				Discharge (t/y)	Concentration(%)					
1	Methanol	Yulin natural gas chemical factory	430,000	1204000	99%	Southern suburbs of Yulin	Yulin	-		Natural gas to methanol
2	Methanol	Shaanxi Shenmu chemical industry company	Designed 0.6 million, 0.2 million in phase I complete	1680000	99%	Shenmu Jingjie industrial development zone	Yulin	Shenmu		Coal to methanol
3	Methanol	Yanzhou coal mining company	Designed 2.3 million, 0.6 million in phase I	6440000	99%	Yuyang District Caojiatan Town	Yulin	Caojiatan		Coal to methanol
4	Methanol	Yulin enterprise zone methanol project	600,000	1680000	99%	Yulin enterprise zone	Yulin	Enterprise zone		Coal to methanol
5	Methanol	Changqing oilfield methanol company	100,000	280000	99%		Yulin	Jingbian		
6	Methanol	Yanchang oil company	1,800,000	5040000	99%		Yan'an	Huangling, Fuxian		Yan'an government, Yanchang Oilfield company and the Hong Kong and China Gas Company Limited cooperate in construction
7	Methanol	Shaanxi Shanjiao chemical Co., LTD	200,000	560000	99%		Tongchuan	Meijiaping	http://www.sxcoking.com/Enterp ise/?Id=40	
8	Methanol	Shaanxi Xianyang chemical Co., LTD	600,000	1680000	99%		Xianyang	Weicheng	http://www.ychb.gov.cn/skin/qi e/articledisp.asp?id=329	Coal to methanol
9	Methanol	Shaanxi Heimao coking Co., LTD	100,000	280000	99%		Weinan	Hancheng	http://heimaocoking.l247.bizcn.com/	
10	Methanol	Weihe coal chemical group	200,000	560000	99%		Weinan	Linwei	http://www.fert.cn/company/200 6/20066912295271094.html http://www.wei-he.com.cn/	
11	Methanol	Shaanxi Changqing 0.6 million tons methanol project	600,000	1680000	99%		Baoji	Fengxiang		
12	Methanol	Shaanxi Xianyang Xingping synthetic ammonia to methanol project	300,000	840000	99%		Xianyang	Xingping		
13	Methanol	Yan'an Yanchang natural gas to methanol, dimethyl ether project	600,000	1680000	99%		Yan'an	Yanchang		Have not started
14	Methanol	Shaanxi Chenghua Co., LTD	20,000	56000	99%		Hanzhong	Chenggu	http://www.sxchgf.com/newEbiz EbizPortalFG/portal/html/Genera lContentShow.html?GeneralConte	
15	Methanol	Shaanxi Huashan chemical Co., LTD	40,000	112000	99%		Weinan	Huaxian	http://www.hshggroup.com/comc tent_detail/&FrontComContent_li st01-	

Appendix Ⅱ: Ethanol plant in Shaanxi

Name	Yield (ton/year)	CO_2 emission		Address	City	County	Website	Remark			
		Discharge (t/y)	Concentration(%)								
Shaanxi Baoji alcohol factory	350 thousand tons of beer, 30 thousand alcohol	30000	99.9%	Baoji Guozhen railway station	Baoji	Baoji	http://www.cheminfo.gov.cn/UI/yellowpage/Shows.aspx?hyi 441				
Xi'an Sanqiao alcohol factory				Shaanxi Xi'an Weiyang District Sanqiao Town	Xi'an	Weiyang	http://ccn.mofcom.gov.cn/343612				
Hanzhong Laojie alcohol Co., LTD				Shaanxi Hanzhong Hantai District Hanwu Road	Hanzhong	Hantai	http://sp.woisoso.cn/corp-420822.html				

Appendix Ⅲ: Dimethyl ether plant in Shaanxi

No.	Type	Name	Yield (ton/year)	CO_2 emission		City	County	Website	Remark	
				Discharge (t/y)	Concentration(%)					
1	Dimethyl Ether	Yulin 1 million tons methanol to dimethyl ether project	200,000	2500000		Yulin	-			
2	Dimethyl Ether	Yulin Fugu 1.5 million tons methanol, 1 million tons dimethyl ether	Investment stage	6500000		Yulin	Fugu			
3	Dimethyl Ether	Yan'an Yanchang natural gas to methanol, dimethyl ether project	700,000	1750000		Yan'an	Yanchang		Have not started	
4	Dimethyl Ether	Weihe coal chemical group	10,000	25000		Weinan	Linwei			
5	Dimethyl Ether	Xianyang 1 million tons coal to dimethyl ether project	1,000,000	2500000		Xianyang	-			
6	Dimethyl Ether	Shaanxi Pucheng 1 million tons dimethyl ether project	1,000,000	2500000		Weinan	Pucheng	http://www.zhaobiao.gov.cn/projectinfodtail/23742726.html		
7	Dimethyl Ether	Xi'an Hanyu chemical Co., LTD	-	-		Xi'an	-			
8	Dimethyl Ether	Shenmu Taineng chemical Co., LTD	-	-		Yulin	Shenmu			

Appendix Ⅳ: Hydrogen plant in Shaanxi

Name	Yield (ton/year)	CO_2 emission		City	County	Website	Remark			
		Discharge (t/y)	Concentration(%)							
Shaanxi Shenmu Tianyuan chemical Co., LTD	90,000	436435.7143	99%	Yulin	Shenmu	http://www.huaxigas.com/gsyj_js.asp				

Appendix Ⅴ: Ammonia plant in Shaanxi

No.	Type	Name	Yield (ton/year)	CO_2 emission		Address	City	County	Website	Remark
				Discharge (t/y)	Concentration(%)					
1	Synthetic ammonia	Fugu fertilizer plant	-	-	100%	Fugu Shibangou	Yulin	Fugu	-	
2	Synthetic ammonia	Shaanxi Aoweiqiyuan chemical Co., LTD	300,000	1140000	100%	Yulin Fugu Huangfuzhen	Yulin	Fugu	http://www.sxxmjt.com/show.asp?id=93	
3	Synthetic ammonia	Inner Mongolia Tianrun fertilizer Co., LTD	0.3 million tons ammonia, 0.52 million tons urea	1140000	100%	about 150 km to Yulin	Hohhot	-		
4	Synthetic ammonia	Inner Mongolia Bodashidi chemical Co., LTD	1 million tons ammonia, 1 million tons urea, 1.2 million tons alkali project	3800000	100%	Nalinhe chemical zone, about 80 km to Yulin	Erdos	Uxin Banner Nalinhe	http://shop.cnsb.cn/index-1185350.html	
5	Synthetic ammonia	Inner Mongolia Erdos fertilizer project	2 million tons ammonia, 3.5 million tons urea	7600000	100%	about 120 km to Yulin	Erdos	-		
6	Synthetic ammonia	Mizhi nitrogen fertilizer plant	30,000	114000	100%		Yulin	Mizhi		
7	Synthetic ammonia	Hanzhong Yangxian nitrogen fertilizer plant			100%		Hanzhong	Yangxian	-	
8	Synthetic ammonia	Shaanxi Xianyang Xingping synthetic ammonia to methanol project	300,000	1140000	100%		Xianyang	Xingping		
9	Synthetic ammonia	Shaanxi Heimao coking Co., LTD	100,000	380000	100%		Hancheng	Xizhuang town	http://heimaocoking.l247.bizcn.com/	
10	Synthetic ammonia	Weihe coal chemical group	0.3 million tons ammonia, 0.52 million tons urea	1140000	100%		Weinan	Linwei		
11	Synthetic ammonia	Shaanxi Qinling fertilizer plant	160,000	608000	100%		Baoji	Jintai	http://www.cheminfo.gov.cn/UI/yellowpa /Shows.aspx?hyid=10681	
12	Synthetic ammonia	Shaanxi Shanhua fertilizer Co., LTD	0.26 million tons ammonia, 0.32 million tons urea	988000	100%		Weinan	Huaxian	http://www.fert.cn/company/20066/20066 2295258702.html	
13	Synthetic ammonia	Shaanxi Chenghua Co., LTD	0.12 million tons ammonia, 0.14 million tons urea	456000	100%		Hanzhong	Chenggu	http://www.sxchgf.com/newEbiz1/EbizPor LEG/portal/html/GeneralContentShow.html	
14	Synthetic ammonia	Shaanxi Huashan chemical Co., LTD	0.26 million tons ammonia, 0.32 million tons urea	988000	100%		Weinan	Huaxian	http://www.hshggroup.com/comcontent_de il/&FrontComContent_list01-	

Appendix Ⅵ: Calcium carbide plant in Shaanxi

No.	Type	Name	Yield (ton/year)	CO2 emission		Address	City	County	Website	Remark
				Discharge (t/y)	Concentration(%)					
1	Calcium carbide plant	Shenmu Shenxin calcium carbide plant	20,000				Yulin			
2	Calcium carbide plant	Fugu Huanghe Social Welfare chemical factory	20,000				Yulin		http://www.baiinfo.com/article/default/127/3679510.html	
3	Calcium carbide plant	Fugu Fangzheng chemical Co., LTD	20,000				Yulin			
4	Calcium carbide plant	Fugu Huifeng chemical Co., LTD	20,000				Yulin			
5	Calcium carbide plant	Fugu Tianqiao calcium carbide plant	20,000				Yulin			
6	Calcium carbide plant	Fugu Xinlong chemical Co., LTD	20,000				Yulin			
7	Calcium carbide plant	Fugu Dongshan calcium carbide Co., LTD	20,000				Yulin		http://hzqdongshandianshi.net114.com/	
8	Calcium carbide plant	Fugu Yuejin calcium carbide plant	20,000				Yulin			
9	Calcium carbide plant	Fugu Changcheng ferroalloy works	20,000				Yulin			
10	Calcium carbide plant	Fugu second calcium carbide plant	20,000				Yulin			
11	Calcium carbide plant	Tianqiao corp. Fugu calcium carbide Co., LTD	20,000				Yulin			
12	Calcium carbide plant	Shenhua electric chemical Co., LTD	20,000				Yulin			
13	Calcium carbide plant	Fugu calcium carbide plant	20,000				Yulin			
14	Calcium carbide plant	Huayuan electric power Co., LTD	10,000				Xi'an		http://cn.made-in-china.com/showroom/sxhyqs/product-	
15	Calcium carbide plant	Weibei calcium carbide plant	30,000						http://www.chengcheng.gov.cn/Governmen PublicInfoShow.aspx?ID=561	
16	Calcium carbide plant	Fugu Fuda welfare calcium carbide plant	20,000							
17	Calcium carbide plant	Qishan calcium carbide plant	20,000							
18	Calcium carbide plant	Baoji calcium carbide plant	20,000							
19	Calcium carbide plant	Jingyang Bayi calcium carbide plant	20,000							
20	Calcium carbide plant	Hanjiang chemical Co., LTD	20,000							
21	Calcium carbide plant	Xi'an thermoelectricity corp.	20,000							

Opportunities for CO_2 Enhanced Oil Recovery (EOR) in Shaanxi Province and the Northwest of China

Supporting early Carbon Capture Utilisation and Storage development in non-power industrial sectors

1. Introduction

Enhanced Oil Recovery (EOR) techniques are a set of processes that have been applied to mature and depleted oil reservoirs since the 1970s in order to increase the production over what is normally achieved using traditional oil recovery techniques. While conventional oil recovery methods usually extract around 20-30% of the Original Oil In Place (OOIP), application of an EOR technique can increase this amount to up to 60%; however, the process is known to be energy intensive. Commercial methods of EOR can be grouped into three main categories of thermal recovery, chemical injection and gas injection. One of the gas injection methods is based on the use of carbon dioxide CO_2 and is known as CO_2-EOR; this is the most successful and widely used of the EOR methods. CO_2 is pumped into the oil reservoir to reduce viscosity and improve the flow of oil. Under the right physical conditions, CO_2 will form a miscible mixture with the crude oil, which leads to the reduction of interfacial surface tension. After the oil-CO_2 mixture is brought to the surface the CO_2 is separated from the oil and recycled for further injection into the reservoir. A consequence of the operation is that a proportion of the injected CO_2 remains underground in the reservoir which, when CO_2 from anthropogenic sources is used, contributes to a reduction of greenhouse gas emissions.

Enhanced Coal Bed Methane (ECBM) recovery is another method that can use gas injection to enhance hydrocarbon recovery. This process works by injecting CO_2, N_2, or a mixture of both into unmineable coal seams, the CO_2 then replaces methane adsorbed on to the coal surface and the N_2 reduces the partial pressure of methane in the reservoir resulting in its desorption. The coal surface desorption of methane leads to higher recovery and the CO_2 adsorption results in its sequestration; however, CO_2 injection can lead to a reduction in reservoir permeability that is caused by swelling of the coal matrix.

Shaanxi Province, China has excellent potential for early opportunity CCUS projects because the region is rich in oilfields, coal and coal-bed methane resources. The potential for improved recovery using CO_2-EOR and CO_2-ECBM is believed to be significant and the CO_2 storage potential is believed to be vast. Furthermore, the province has readily available sources of high purity CO_2 from its large coal-to-liquids industry, as well as from the fertiliser industry and others [1]. Successful demonstration of CO_2-EOR using industrial sources in North America has shown that the main technical barriers of this technology can be overcome. CO_2-ECBM is a relatively less developed technology, therefore its technical barriers are considered to be a greater challenge in comparison to CO_2-EOR. Significant barriers to CCUS deployment in Shaanxi Province are believed to relate to the initial capital costs and the lack of policy measures and regulatory framework; however, once these are in place, the economic potential is considered to be high.

Increasing interest in CCUS opportunities such as CO_2-EOR and CO_2-ECBM in China and across the world can be expected in the future. Higher fossil fuels prices will make enhanced recovery operations more attractive for investment while emissions trading schemes could provide additional financial incentives. Clean development mechanism projects could be initiated in developing countries to cover capital and running cost. The technologies are likely to play an important role in reducing anthropogenic CO_2 emissions underground while simultaneously improving the security of energy supply by enhancing and prolonging oil and gas production. Demonstration of early CCUS opportunities can also be expected to encourage the development, demonstration and deployment of advanced power generation technologies with application of carbon capture and storage.

1.1 Fundamentals of CO_2-EOR and CO_2-ECBM

Oil recovery techniques have been typically considered in three categories of primary, secondary and tertiary oil recovery. Primary recovery techniques are usually applied at the beginning of the production and can rely on natural mechanisms such as the pressure in the oilfield for extraction. After the natural reservoir pressure reduces, pumps are used to extract additional oil. Secondary recovery techniques are applied subsequent to primary recovery and are based on the application of external energy to the reservoir in the form of an injected fluid to increase the reservoir pressure; very often the injected fluid used is water (water flooding). Tertiary oil recovery methods, otherwise known as EOR, consist of sophisticated operations that are applied after secondary methods and towards the end of an oilfield's life; CO_2-EOR is one of these methods. Very often more than a third of the OOIP remains in the reservoir after primary and secondary recovery techniques have been applied. CO_2-EOR can be applied to target this remaining oil and produce an additional 5-15% of the OOIP [2]. The residual oil exists as droplets trapped in the pores of reservoir rock or oil films that surround rock grains. The aim of CO_2-EOR is to mobilise these dispersed oil droplets via the injected CO_2 entering the reservoir and moving through the pore space to form an oil bank that is swept towards the producing wells. CO_2-EOR should also work on the macro scale to effect large volumes of oil in the reservoir [3].

To be successful, CO_2-EOR requires a careful consideration of the chemical and physical interactions between CO_2, oil and rock that create favourable reservoir conditions and increase oil recovery. When the injected CO_2 and oil mix to form a miscible fluid the interfacial tension between the two initial phases effectively disappears, enabling the CO_2 to displace the oil from the rock pores and push it towards the production wells; this is known as miscible CO_2 displacement and is the most common form of CO_2-EOR. When CO_2 dissolves in the oil it causes oil swelling that reduces its viscosity and improves its flow. In addition, the mobility characteristics of oil and CO_2 should be considered because the movement of CO_2 in the reservoir has a tendency to be faster than oil. For effective CO_2-EOR, the mobility of the CO_2 should be similar to that of the oil. The mobility of the CO_2 and oil phases is dependent on how the presence of other fluids hinders their flow and their viscosity. When the mobility of CO_2 is higher than that of oil, the fluid flow becomes unstable which can lead to the early breakthrough of CO_2 at the production well and [2]. As a consequence, further injected CO_2 follows the same fingered path to early breakthrough and therefore does not sweep the maximum possible volume of the reservoir, which leads to a reduction in the overall efficiency of the process. In order to mitigate this negative tendency, CO_2 injection is often alternated with water injection, known as Water Alternating Gas (WAG) flooding.

For miscible CO_2 displacement, supercritical CO_2 is used at high pressure (exhibiting the density of a liquid and the viscosity of a gas). However, CO_2 does not instantly form a miscible mixture with oil; rather the miscible mixing is a gradual process, which develops as the CO_2 flows through the reservoir. The miscibility of CO_2 and crude oil in the reservoir is strongly affected by pressure. Below the Minimum Miscibility Pressure (MMP), oil and CO_2 will no longer form a miscible mixture. As reservoir temperature increases, the density of CO_2 decreases and the required MMP will increase. In some cases, it may be necessary to re-pressurise the reservoir via water injection so that the MMP can be reached. The MMP can also be affected by the composition of crude oil and the purity of CO_2.

CO_2-EOR can be also be effective under conditions when the MMP cannot be reached and the CO_2 and oil do not fully form a miscible mixture, such with low pressure reservoir or for heavy crude oil where the mechanism for oil recovery is usually associated with gravity displacement [4]. Although this is known as immiscible CO_2 displacement method, CO_2 may partially dissolve in the oil; some oil swelling can occur and the oil viscosity can be significantly reduced. The immiscible CO_2 displacement method is much less widely used compared to the miscible CO_2 displacement method, primarily due to the poor process economics. Large quantities of CO_2 are required, which are not easily recovered for recycle, and up to ten years wait can be required until an improvement in oil recovery occurs. The method could nevertheless be expected to receive increased attention, in the context of atmospheric CO_2 emission abatement, due to its ability to geologically store large quantities of CO_2 [2].

Coal Bed Methane (CBM) is a useful energy resource that can be a significant supplement to conventional natural gas supplies. Usual methods of CBM recovery involve depressurising the coal seam by drilling wells into it and then pumping out water. The depressurisation of the coal seam leads to methane that is adsorbed into the coal matrix being released. The methane can then be extracted, separated from water at the surface and then used in the same way as natural gas. The desorption and recovery of CBM can be enhanced by the process of gas injection into the coal seam.CO_2, N_2 or mixtures of two (such as flue gas) are the main gases considered for injection. CO_2 exhibits a greater sorption capacity on coal compared to methane and therefore displaces the CBM from the sorption sites on the coal matrix surface causing its release to the cleat system. N_2, on the other hand, has a lower sorption capacity than methane on coal surfaces. Injection of N_2 is used to lower the partial pressure of methane in the free gas phase in the pore space which induces desorption. The relative sorption capacity between the gases is strongly dependent on coal rank [5].

It is well known that as gas is released from a coal reservoir, the coal matrix shrinks; this causes the cleats to open and therefore significantly increases the level of coal cleat permeability. This process is also believed to work in reverse, whereby gases with large adsorptive capacity, such as CO_2, can cause swelling of the coal and considerable reduction permeability. This can lead to a severe reduction of well injectivity of CO_2, which would restrict the overall effectiveness of the ECBM process and can severely hamper economic performance. Further research and pilot demonstrations are required in order to understand how the benefits of ECBM can be gained while minimising the negative impacts.

1.2 Features of this report

The aim of this report is to assess the potential of the oilfields and unmineable coal beds located in Shaanxi Province in hosting an early opportunity CO_2 utilisation demonstration project. The report is structured as follows:

- Initially, the report reviews the status of CO_2 utilisation for enhanced hydrocarbon recovery in relation to China and throughout the world. An inventory of CO_2 utilisation opportunities in Shaanxi Province is presented – this has been compiled from a combination of expert knowledge, literature reviews and stakeholder surveys. A description of the consultation with stakeholders (e.g. oilfield operators, government agencies and academia) via surveys and workshop meetings is presented in terms of CO_2 utilisation potential and implementation challenges.

- The report then examines the viability of the CO_2 utilisation options. One of the main requirements of this project is to identify potential matches of CO_2 sources and sinks based on a number of technical, economic and geographic considerations. Screening criteria of oilfields and coal bed methane sites for their compatibility with CO_2-EOR and CO_2-ECBM is discussed.
- Finally, the report presents an outlook for EOR and other utilisation options in Shaanxi, which is one of China's most important regions for oil and CBM reserves. The prospects for CO_2 storage and increased hydrocarbon recovery in the region are reviewed.

2. Status of CO_2 utilisation

This section reviews current CO_2 utilisation operations globally and with focus on those in China. The main oil basins/coal fields currently supporting CO_2 utilisation operations in China are identified and characterised, along with those currently under construction or in the planning stage. To provide an inventory of CO_2 utilisation options of Shaanxi Province, an overview of oilfields and coal basins with the potential to host a CO_2 utilisation demonstration project is presented. The section also includes some of the key findings on the technical, policy, legislative and regulatory challenges of implementing a CO_2EOR or CO_2-ECBM project. CO_2-EOR projects have been successfully demonstrated at commercial scales for over 30 years but have mainly used natural subterranean sources of CO_2, which are high in purity and low in cost. Only a small fraction of CO_2-EOR projects utilise CO_2 from anthropogenic sources; however, interest and rate of usage from this source is increasing due to the limited supply of natural CO_2 throughout the world. Traditional approaches to CO_2-EOR have aimed to minimise the amount of CO_2 used per incremental barrel of oil produced and recycle any CO_2 recovered at the production well for economic reasons; this is in contrast to the aims of geological storage of CO_2 for its emissions abatement. This section reviews techniques and ways to encourage the co-optimisation of CO_2-EOR/CO_2-ECBM with CO_2 geological storage.

2.1 Overview of CO_2 utilisation opportunities in China and Shaanxi Province

A number of potential geological reservoirs can be considered to store captured CO2 [1]. These storage options include depleted oil and gas fields; CO2 enhanced oil recovery (EOR); CO2 enhanced gas recovery (EGR); CO2 enhanced coal-bed methane recovery (ECBM); deep saline aquifers; and some other storage options such as mineral carbonation.

2.1.1 CO_2 Enhanced Coal Bed Methane Recovery

CO_2 underground storage is an effective measure to reduce CO_2 in atmosphere and alleviate greenhouse effect. CO_2-ECBM can reduce CO_2 emission as well as promote coal bed methane (CBM) yield and decrease the cost of CO_2 underground storage. CO_2-ECBM is a safe and reliable way to store CO_2 by adsorbing CO_2 in coal matrix. China has abundant coal resources; coal seams are widespread all around China. So CO_2-ECBM can be the top choice of CO_2 underground storage. According to coal and CBM exploration data in China, reserves distribution of different coal, and replacement ratio of CO_2 and CH4, we conducted a preliminary evaluation of CO_2 storage capacity in coal seams which are about 300~5000 meters deep and rich of CBM. The result indicated that minable CBM in China can reach $1.632\times10^{12}m^3$, meanwhile that would be able to store 120.78×10^8 tons CO_2 which is about 3.6 times of China's CO_2 emission in 2002.

2.1.2 CO_2 Enhanced Gas Recovery

Nearly depleted gas fields can be considered for CO_2 storage in the void space freed by exploitation. Existing infrastructures such as wells may be partially re-used. Since these reservoirs have contained gas for thousands of years, they are expected to store safely CO_2 for a very long time. The storage capacity can be estimated from the original gas in place or from ultimate recoverable reserve volumes, assuming the void space freed by the production is fully filled with CO_2 and has not been flooded by water.

The pressure inside the reservoir drives usual exploitation of gas fields, but when pressure is no longer sufficient to drive fluid towards the well bore, exploitation is hampered, while a large proportion of the hydrocarbons still lies underground. In the case of oil, the 'associated gases', i.e. the dissolved light hydrocarbons, after being separated out from the oil, can be reinjected to maintain the reservoir pressure. An option is to inject CO_2, which displaces the hydrocarbons and in the case of oil, modifies the viscosity and enhances the recovery. This process is designated by CO2-EGR. Part of the injected CO_2 (say about half) breaks through into the produced gas, and is recycled after separation, while the other part is 'fixed' in the gas reservoir.

2.1.3 Others

FOOD INDUSTRY: In the food industry, CO_2 is used for food refrigeration, sterilisation, preventing mildew and retaining freshness, etc. In order to adjust the competition in international food market and meet the domestic high-end food preservation needs, this will be a potential market of liquid and solid CO_2. CO_2 can also be used as additive in soda drink, beer, cola and carbonated beverages. CO_2 consumption in west Europe is 1.6 million tons/year, 80% of this is liquid CO_2. The CO_2 is mainly used for carbonated beverage and food, then for weld and refrigerated transport. Germany produces the most CO_2 by separating them from natural gas – there are more than 30 liquid CO_2 factories are in Germany. CO_2 consumption, which consists of 80% liquid CO_2 and 20% solid CO_2, will increase by 3–4% in the next few years in west Europe. In China, drink industry is the largest CO_2 consumption market, which takes about 30%. Our drink consumption per person is less than 5 kilos/year, while in the USA it is 150 kilos/year, and in west Europe it is 110 kilos/year. As people's living standards in China improve, CO_2 consumption in the drink industry will increase substantially. On the basis of the drink consumption in the USA, CO_2 consumption in the drink industry could be millions of tons per year in China.

Plastic material: Using CO_2 as chemical feedstock to produce plastic products has taken shape globally. In recent years 110 million tons of CO_2 has been sequestrated through chemical methods every year. Urea is the largest product sequestrating CO_2, consuming more than 70 million tons of CO_2 per year. Inorganic carbonate is the second largest, consuming 30 million tons CO_2 per year. Hydrogenation of CO_2 to synthesise CO also consumes 6 million tons of CO_2. Alongside this, 20 thousand tons CO_2 is used to synthesise salicylic acid and propylene carbonate, which is used for drug manufacturing.

Synthesized urea with CO_2 and ammonia is the most successful example of sequestrating and using CO_2. Based on urea, we still can produce dimethyl carbonate with CO_2, making urea an effective carrier of CO_2. Replacing phosgene by CO_2 to synthesise high value-added chemical feedstock (dimethyl carbonate, isocyanate, methyl methacrylate, etc.) can realise cleaner production; meanwhile it can react at mild conditions so as to improve the economy and security of the process.

At present, CO_2-based plastic represented by CO_2 and epoxide copolymers is also a hot issue. This kind of plastic is biodegradable which makes it helpful to resolve the 'white pollution' problem. China National Offshore Oil Corporation (CNOOC) and Inner Mongolia Melic Sea High-Tech Group Company, representing the most advanced CO_2-based plastic industrial technology in the world, have built two production lines of thousand-tons-level. Henan Tianguan Group has built a CO_2 copolymer pilot plant with its self-initiated catalysis system. Low molecular weight of CO_2 copolymer technology, researched by Guangzhou Institute of Chemistry, Chinese Academy of Sciences, has been used in Taixing, Jiangsu. This technology use low molecular weight of CO_2 and epoxide copolymer as feedstock of Polyurethane foam materials.

2.2 Global status and developments of CO_2-EOR and CO_2-ECBM

CO_2-EOR technologies have been used at commercial scale by the oil and gas industry for over 30 years. The process was pioneered in the Permian Basin of West Texas and New Mexico using natural sources of CO_2 for oilfield injection and this remains the world's largest CO_2-EOR producing region. The extensive CO_2 pipeline infrastructure that has emerged in the region does deliver the CO_2 requirements to the EOR projects. Other regions in the North America have developed CO_2-EOR projects, especially in the Gulf Coast and the Rocky Mountains. Natural CO_2 sources account for the majority of supply to North American CO_2-EOR projects, with a supply of 45 million tons/year. However, the natural CO_2 reserves can only meet a small fraction of potential for EOR and there is consequently a strong interest in obtaining CO_2 from industrial sources. The Shute Creek gas processing plant at the La Barge field in Wyoming is the largest single point source of anthropogenic CO_2 used for EOR in North America and amounts to a 4 tons/year supply [6].

A number of other CO_2 flooding projects have been implemented in several other countries outside of North America including Hungary, Turkey, Trinidad, Brazil and Russia. In Hungary, several field-scale CO_2-EOR applications have been implemented, ranging from immiscible displacement in sandstone and karstic reservoirs, to miscible displacement in metamorphic and mixed rock reservoirs [7]. A successful application of immiscible CO_2-EOR has taken place in the Bati Raman Oilfield in southeastern Turkey; approximately 1 million tons/year of naturally sourced CO_2 is transported via a 90km pipeline to this operation [8]. Pilot-scale EOR trials, whixh ran from 1973–1990 at the Forest Reserve and Oropouche fields in Trinidad, produced medium oil using industrially sourced CO_2 from ammonia (oil and gas journal survey). In Brazil, small scale CO_2-EOR has been taking place since 1987 at the Recôncavo Basin using CO_2 collected from an ammonia plant and an ethylene oxide production facility. Large-scale pilot-scale EOR tests were carried out in Russia from 1980–1990, which utilised CO2, and combustion gases formed at different petrochemical production plants [9]. A CO_2 pilot injection project has been reported at the Ivanić oilfield in Croatia. The results, obtained from 2001–2006, helped to define the larger application of CO_2-EOR in this country by using anthropogenic CO_2 sources [10].

In China, several experimental pilot-scale EOR projects are ongoing at Liaohe, Shengli, Dagang, Zhongyuan, Daqing and Jilin oilfields [11]:

- **Liaohe Oilfield Complex.** The pilot scale project of CO_2/flue gas injection for EOR has been conducted at Liaohe oilfield complex since 1998. The application has involved the injection of boiler flue gas containing 12–13% CO_2 and steam without premixing the two fluids. After a preliminary test injection, the well was closed for a number of days to allow the diffusion and penetration of the injected gases throughout the reservoir. A significant improvement in oil recovery of 50–60% was observed with the steam-flue gas injection [12].

- **Shengli Oilfield Complex.** A pilot scale CO_2-EOR project began at the Shengli Oilfield complex in 2007. Sinopec China plans to expand post-combustion CO_2 capture at the existing Shengli power plant in Shangdong Province for use in EOR. The retrofitted absorption plant will capture around 1 million tons/year of CO_2 for pipeline transport over a short distance to the EOR site. The large-scale project is expected to come online in 2014 [11] [13].

- **Dagang Oilfield Complex.** A CO_2-EOR pilot test at the Kongdian reservoir of the Dagang Oilfield complex began in 2007 and lasted for 1.5 years. The operation used natural gas with 20% CO_2 obtained from a nearby natural gas field which was injected into a single well. Oil production reportedly improved from 13.6 to 68 barrels per day [11]. A demonstration project is currently under construction by China Huaneng group that aims to capture CO_2 from a 400 MW Integrated Gasification Combined Cycle (IGCC) power station, which will be used for EOR in Dagang Oilfield. The construction is to be completed in 2016 [14].

- **Zhongyuan Oilfield.** The China National Petroleum Corporation began capturing CO_2 from an oil refinery and injecting it into its Zhongyuan Oilfield. Few details are available in the literature but the company has reported capturing and injecting 20,000 tons/year of CO_2 [11].

- **Daqing Oilfield Complex.** Field tests for immiscible CO_2 floods have taken place at Daqing Oilfields since the early 90s [15]. In 2008, the governments of Japan and China agreed to cooperate in a project to capture 1–3 million tons/year of CO_2 from the Harbin thermal power plant in Heilungkiang Province for EOR injection in the Daqing Oilfield. The project will involve CO_2 transportation in a ~100 km pipeline.

- **Jilin Oilfield Complex.** PetroChina established a pilot scale CO2-EOR and storage project in Jilin Oilfield in 2007. The project uses a natural gas source containing 22.5% CO_2 which is now being stripped during the production process and condensed before being injected into several oilfields at a rate of 200-300,000 tons/year. Oil recovery will be enhanced by 10–20%.

CO_2-ECBM is currently at an early stage of technical development. Several projects exist at the pilot scale and micro-pilot scale worldwide. Burlington Resources have been operating a commercial pilot application of CO_2-ECBM located in the Allison production unit in the San Juan Basin in the southwestern United States. The Allison unit pilot injects around 85,000 m^3/day of naturally occurring CO_2 from the McElmo Dome field in southwestern Colarodo. The pilot performance in this project has been varied, with some production wells showing improved methane recovery whereas others show a decline in performance following CO_2 injection. Another CO_2-ECBM project has taken place at the micro-pilot scale in Alberta, Canada with the objective of establishing a commercial pilot project. The well was monitored during the injection of synthetic flue gas (12.5% CO_2 /87.5% N_2) and the performance indicated that the permeability increased steadily during the injection period [16] [17].

Additional micro-scale CO_2-ECBM projects have taken place in Poland and Japan. The RECOPOL project involved the first CO_2-ECBM demonstration in Europe and began in 2003. During the project, some difficulties were encountered following CO_2 injection including a reduction in permeability, likely due to coal swelling, and the observation of a rise in the CO_2 content of the production gas [18]. In Japan, another micro-pilot scale project was carried between 2004 and 2007 at the Ishikari coal basin on the northern Hokkaido Island. The project involved a variety of tests with an injection well and multiple production wells. During the tests, CO_2 injection clearly enhanced gas production; however, low injectivity was experienced after the CO_2 flood which was likely caused by the reduction in permeability induced by coal swelling. Subsequent N_2 flooding was found to improve well injectivity but only temporarily and the permeability did not return to its initial value after repeated CO_2 and N_2 injection [19].

China is believed to hold large potential for gas injection technology for ECBM production. A joint CO_2-ECBM project between the China United Coal Bed Methane Corporation (CUCBM) and the Alberta Research Council of Canada was initiated in March 2002 and ran until December 2007. The micro-pilot scale project took place at an existing well in the Qinshui basin of Shanxi Province, China. This is the only CO_2-ECBM project to have taken place in China so far [20]. Qinshui Basin contain high ranked semi-anthracite/anthracite coal, covers an area 24,000 km^2 and is believed to contain CBM resources of 5.5 trillion sm^3. The project objectives of measuring data while using one injection and one production well and then evaluating this data to obtain estimates of reservoir properties and sorption behaviour were fulfilled. In addition, a calibrated numerical model of the reservoir was developed to predict multi-well pilot performance and level of production enhancement with CO_2 injection [21].

2.3 Required purity levels for CO_2-EOR and CO_2-ECBM

For the purpose of CO_2-EOR, CO_2 purity should be more than 94-95 vol.% in order to achieve miscible conditions in the oil reservoir. The MMP, reservoir depth and the API gravity of the oil determine if the reservoir is suitable for CO_2-EOR. SO_2, H_2S and C_3+ species impurities in the CO_2 will decrease the MMP whereas O_2, N_2, Ar and NO impurities will increase the MMP. For CO_2 transport via pipeline to an EOR site, consideration must be given to the impact the impurities could have on pipeline corrosion or phase change of the transported fluid [22]. The presence of SO_2 as an impurity could accelerate pipeline corrosion since this gas forms an acid when dissolved in water. Water levels should therefore be reduced to a certain level, but to exactly what extent is controversial. An upper limit of 500 ppm of H_2O in the CO_2 stream has been recommended by de Visser et al. [23]. The presence of O_2 with H_2O can accelerate cathodic reaction leading to internal pipeline corrosion. The presence of impurities could result in the formation of a second liquid phase during the transport of supercritical CO_2, which could have consequences of flow instability and cavitation in the pipe. It would also lead to undesirable high and low pressure peaks that oscillate within the pipeline [24]. Most EOR operators recommend levels of oxygen to be below 10 ppm for reservoir safety reasons. In addition, impurities in the CO_2 stream may have an impact on sequestration. The CO_2 impurities can have the same corrosion impacts on well injection equipment as they do on pipeline equipment, which could affect injection well integrity. The impact that CO_2 impurities have on the subterranean environment is uncertain and is an area that requires further research. The volume occupied by CO_2 impurities in a storage site would also contribute to a reduction in storage efficiency.

Information regarding acceptable limits for impurities in CO_2-ECBM is much sparser in comparison to that for CO_2-EOR, although recommendations made with regards to compression and pipeline transport will be the same. ECBM can accommodate high levels of N_2 since this gas is also effective for the methane recovery process. However, the use of flue gas instead of CO_2 has a much higher energy requirement for compression. H_2S and SO_2 are undesirable in CO_2-ECBM because they have higher adsorption affinities than CO_2 and so would preferentially adsorb onto the coal surface and hence reduce the storage capacity [25]. Oxygen is also an unwanted impurity since it reacts irreversibly with coal to reduce the area for sorption and storage capacity for CO_2.

2.4. Opportunities for increasing CO_2 storage with CO_2-EOR

The overall objectives of CO_2-EOR and CO_2 storage are somewhat different. In traditional CO_2-EOR methods, the aim has been to maximise oil production and because the purchase of CO_2 constitutes a significant operational cost, considerable efforts have been made in reservoir engineering design to minimise the amount of CO_2 utilised per barrel of oil recovered. If the objective is instead to maximise the amount of CO_2 stored at the end of oil recovery operations while maximising oil recovery the engineering design approach would change significantly.

In current CO_2-EOR projects, a significant fraction of the injected CO_2 remains in the reservoir but some is recovered at the production well. This is usually separated from the oil, recompressed and injected back into the reservoir. The CO_2 that remains in the reservoir can become trapped in pores or channels of the reservoir rock from where it has displaced oil. Some CO_2 dissolves into oil and water that remains there unless the reservoir is depressurised; even so, the reservoir could not be completely depressurised and the CO_2 in solution would therefore remain there permanently. The CO_2 storage capacity in EOR is a function of the recovery factor, the OOIP and oil shrinkage [26]. A further factor that can influence the storage capacity is the efficiency with which the injected CO_2 displaces fluids in the pore space. A simple strategy to increase CO_2 storage with CO_2-EOR is to displace as much oil and water as possible and replace it with injected CO_2 in the pore space and swept zone. Several approaches for increasing CO_2 storage in EOR have been put forward by Jessen *et al*. [27] and in a report prepared by Advanced Resources International Inc. and Melzer Consulting for the Department of Energy & Climate Change (UK) [6]. A combined version of their recommendations is given below:

- Adjust the composition of the injection gas to maximise CO_2 concentration while maintaining an appropriate MMP.
- Design well completions (e.g. partial completions) or consider horizontal wells to create injection profiles that help to reduce the adverse effects of preferential flow of injected gas through high permeability zones.
- Optimise water injection timing, rates and WAG ratio to minimise gas cycling and maximise gas storage.
- Consider CO_2 injection into aquifers or residual oil zones that underlie main oil pay zones where the gas would otherwise flow rapidly to the producing wells
- Repressurise the reservoir when the production life of the field is over.
- Use ‘next generation’ technology to increase the volume of injected CO_2, optimise well design and placement, improve mobility ratio between CO_2/water and residual oil, and extend the

miscibility range; these could help achieve higher oil recovery efficiency as well as increase the CO_2 storage potential.
- Deploy CO_2 injection earlier in field development. This can result in incremental and faster oil recovery. Improved utilisation of CO_2 storage capacity is also achieved.
- Use any of these approaches in combination with extra storage in other geological formations accessible from the same CO_2 injection wells and surface infrastructure used for CO_2-EOR.

2.5. Environmental impact of CO_2-EOR and CO_2-ECBM

Insight into the environmental impact associated with CO_2-EOR and CO_2-ECBM is essential to ensure that they can be applied as safe and effective technologies. Research is therefore being conducted to evaluate the likelihood and potential consequences of leaks, slow migration and induced seismicity [28]. Minimal environmental problems have been experienced so far in up to four decades of CO_2-EOR operations and it is believed that rock formations are likely to retain over 99% of the injected CO_2 for over 1000 years [3]. However, the potential risks should not be disregarded.

Large-scale releases of CO_2 can occur naturally from volcanoes. As CO_2 is less dense than air, large-scale releases can pose an asphyxiation risk to humans and animals. In 1986, a large-scale CO_2 release proved catastrophic at Lake Nyos in Cameroon. However, it is highly unlikely that such huge CO_2 releases would occur from a geological CO_2 storage site because injected CO_2 will tend to diffuse as it moves away from the injection point in contrast to the accumulation of highly concentrated CO_2 near the surface as was the case at Lake Nyos. The likelihood of large scale CO_2 release from a geological storage site can be reduced with proper site selection, monitoring and operation [28]. To minimise the risk of large sudden CO_2 release from pipeline transport near populated areas, route selection, overpressure protection, leak detection and other design factors all require careful consideration [29].

The slow release of CO_2 from geological storage at an EOR site is possible via rock faults and fractures, or by improperly sealed oil wells. Such slow releases can also occur naturally; however, leaks at CO_2 storage sites could have adverse effects on ecosystems not adapted to exposure to such levels of CO_2; so too could any impurities (e.g., Hg, H_2S) contained in CO_2 arising from anthropogenic sources. The risks associated to slow CO_2 releases are nevertheless believed to be remote since they would diffuse to the atmosphere in a similar way to the CO_2 arising from biological respiration or decomposition of organic matter. The risks associated to CO_2 leakage to the surface can be effectively contained and mitigated by employing proper site selection, engineering design, operational procedures, gas detection and pressure monitoring systems [28].

Migration of fluid within geological formations is difficult to predict despite significant advances in technology and understanding of subsurface fluid behaviour. Upward movement of stored CO_2 or displacement of brine due to increased pressure has the potential to impact on drinking water resources, by increasing its salinity, by leaching trace metals or decreasing pH levels [30] [31]. Such effects have not been observed on current CO_2-EOR projects but a better understanding of these effects on the longer time frame is required.

From a perspective of CO_2-EOR site selection, it is important to understand the risks associated to induced seismicity from injection activities. Gas injection alters the mechanical state of the reservoir due to increases in pore pressure. This might induce fractures or activate faults, so that micro-seismicity or even damaging earth tremors might occur [31]. Although small seismic events have occurred, significant steps can be taken to mitigate the risk including controlling the injection pressure, careful site selection, understanding the storage reservoir's geomechanical properties and the astute positioning of wells and pipelines [28].

Other environmental concerns have been raised regarding the effect of injected CO_2 on subsurface ecosystems. There is currently no data available on these effects and their knock-on effects for the surface ecosphere [32]. More research is required to determine the effects of CO_2 injection on these biological populations.

It can be argued that CO_2-EOR and CO_2-ECBM operations do not present real opportunities to mitigate climate change mitigation since they lead to the further extraction of fossil fuels whose use would contribute to further CO_2 emissions. Life-cycle analyses can be used to quantify effects [33]. Nevertheless, these technologies do present an important intermediate step to the wider deployment of CCS for the reduction of anthropogenic CO_2 emissions.

3. Findings from the government and industry surveys

As China's major province of energy and natural resources, Shaanxi Province has abundant coal resources and is listed as one of China's low carbon demo provinces. Meanwhile, as western underdeveloped province of energy, Shaanxi Province's energy structure is dominated by coal. Heavy chemical industry is still an important pillar industry in promoting economic growth. During the 'Eleventh Five-Year' period, Shaanxi Province exceeded the task of energy saving, but high energy-consuming industries like power, chemical, petrochemical, nonferrous metal, metallurgy and building material contributed more than half of Shaanxi's output value. Contradiction of resources and environment has become increasingly prominent, and this economic pattern is difficult to be fundamentally changed in short term.

CO_2 emission of Shaanxi Province mainly derives from the consumption of fossil fuels. In 2005, it is about 138 million tons and accounts for 2.4% of China's total emissions. Thermal power plant is the main CO_2 emission source in Shaanxi Province, accounting for about 70% of total emissions, followed by cement industry, accounting for about 10%. In addition, ethylene and synthesis ammonia industries account for about 10%, hydrogen production industry accounts for about 0.7%. According to preliminary measurements and estimates, CO_2 emissions from fossil fuels in Shaanxi Province have risen from 138 million tons in 2005 to 209 million tons in 2009, and to 2015 it may reach 450 million tons. Because of the high energy-consumption of coal chemical industry, its large amount of CO_2 emissions and the constantly development of large scale coal chemical projects in the future, CO_2 emissions in 2015 is expected to reach 180 million tons in coal chemical industry. Energy saving and emission reduction will face greater pressure.

Implementing early CCUS demonstrations in Shaanxi Province is of great significance. First of all, Shaanxi Province urgently needs low carbon technology; CCUS is good for developing that technology. Secondly, chemical industry in Shaanxi Province is developed and has a high-purity CO_2 source. It can reduce the cost of implement of CCUS in Shaanxi Province, and it is good for promoting the entire CCUS demonstration. Moreover, Shaanxi provincial government hold a positive attitude to CCUS projects. Implementing early CCUS demonstrations in Shaanxi Province can help to build the image of Shaanxi as a clean energy province.

Surveys from Yanchang Oilfield research institute show that the advantages of Yanchang Oilfield in developing CCUS: first, Yanchang Oilfield owned its own high-purity CO_2 sources; second, it also had oilfields suitable for EOR due to the short distance between the CO_2 sources and sinks (150-200km); and third, the geological condition for oil reservoirs is suitable for EOR. Yanchang Oilfield would like to develop CO2-EOR project and it had applied the national projects to support the full chain of CO2-EOR – the CO2 from chemical plants (high purity) would be transported by tanks to oilfields to enhance oil recovery. Yanchang oil planned to construct the CCUS facility with a scale 100,000 tons per year by the end of 2012, and 400,000 tons per year by the end of 2013. Until now the design of the CO_2 capture equipment had been finished and the evaluation of CO2-EOR had also been completed. The future plan was to develop CO_2 capture with low energy penalty and enforcing cooperation in technology share. Yanchang Oilfield hoped to cooperate with EU and hoped that the EU could provide engineering experiences in EOR.

4. Screening criteria for CO_2 utilisation options

In order to determine CCS demonstration projects, we should consider these factors below:

1. In choosing CCS demonstration projects, whether the CO_2 sources and sinks match each other on the scale should be considered first. We should choose single CO_2 sources to match homologous CO_2 sinks. This can avoid the increase of cost in capture and transport CO_2 from different sources.
2. Secondly, technical feasibility must be considered before every project begins. In deploying CCS demonstration projects, we need to consider the technology maturity of transport and sequestrate CO_2, and if we have any other proven technologies that can be used. For example, in sequestrating CO_2, as CO_2-EOR is a proven technology and has plenty operating experiences, it can be considered first as an effective method of sequestrating CO_2. Of course, CO_2 saline aquifer storage and CO_2-ECBM projects also need to be positively researched and deploy related pilot demonstration projects.
3. In order to make sure that the demonstration projects have good demonstration effect, we should reduce the cost of the project. In detail, we should capture high-concentrated CO_2 to reduce capture cost; CO_2 transportation should also be kept in a cost-effective range; CO_2 sequestration should use EOR, ECBM, because they can bring additional oil/CBM benefits and promote CCS demonstrations.
4. Besides the cost factors, energy consumption factors are also very important. High energy consumption in CCS will lead to more energy consumption; the cost of fuel/feedstock will increase along with that. This is bad for CCS demonstration effect so we should choose high-concentration of CO_2 and low-impurities sources to reduce CO_2 capture cost.
5. As people's awareness of environment protection strengthens, we should also consider the impact of CCS demonstration projects to local environment. For example, whether the sequestrated CO_2 will pollute the underground water and whether the water consumption in CCS demonstration projects will aggravate the local water scarcity.
6. In addition, we should consider social factors such as traffic, policy, safety and public support. In traffic, we need to consider whether the local terrain is fit for pipeline laying, difficulty level of laying pipeline and the transport distance. In policy, we should consider the local policy makers' attitude towards CCS projects-whether it's positive or negative; whether they allow CO_2 storage

in-situ. In safety, we should consider factors like corrosion of CO_2 pipeline, CO_2 transport and storage leakages, etc.

7. In deploying CCS demonstration projects, we should consider the demonstration effect and local public awareness. The demonstration effect is closely linked with demonstration locations, industries, scales and economies, so we should choose those influential locations, industries and appropriate scale to deploy CCS demonstrations. As CCS is a newly sprouted thing that public do not know much about it. They will probably worry about the safety problems (like CO_2 leakage) caused by the projects. So public awareness should also be considered before we deploy the CCS demonstration projects. We can improve the public acceptability by publicity and promotion.
8. At last, as CCS demonstration projects may involve many different enterprise like power plants, chemical plants and oil companies, in choosing potential project for CCS we should consider the difficulty level in coordinate all aspects. We recommend the enterprise, which can be in charge of the whole chain of CCS projects simultaneously, should take responsibility for the CCS demonstration projects.

In conclusion, screening principles of CCS demonstration projects are listed below:

Table 4.1: Basic principle for potential CCS project selection

Sub factors	Technical feasibility	Match of sources and sinks	Economy factors	Energy consumption factors	Environment factors	Traffic factors	Policy factors	Social factors	Safety factors	Demos effect	Difficult level of deploying the project
1.	Technical feasibility	CO_2 emission amount	Capture cost	Capture energy consumption	Contribution to CO_2 emission	Traffic facilities	Local CCS policy	Public awareness	CO_2 transport safety	Demos location	Character of CO_2 source enterprises
2.		Sequestration method and amount	Transport cost	Transport energy consumption	Impact on water resources	Terrain			CO_2 leakage	Demos scale	Character of CO_2 transportation enterprises
3.		Whether the CO_2 sources and sinks match	Sequestration cost	Sequestration energy consumption	Impact on PMIO emissions	Transport distance					Character of CO_2 sequestration enterprises
4.					Other impacts on environment						

Table 4.1 lists various factors in choosing CCUS demonstration projects. These factors can be divided into those necessary and those unnecessary. Necessary factors include the fact that the CO_2 sources and sinks must match each other; the technology must be feasible; these projects must accord with the local policies; and CCUS can be supported by the majority of the public. Unnecessary factors mean those factors that are not necessary, such as economy factors.

In choosing demonstration projects, necessary factors must be satisfied. As to unnecessary factors, we can use a scoring mechanism to come up with the best plan. For instance, when the score of other unnecessary factors are the same, those with a lower cost and energy consumption can be chosen as the final plan. Table 4.2 lists the scoring mechanism for unnecessary factors.

Table 4.2: Scoring mechanism for unnecessary factors in choosing CCUS demonstration projects

	0	1	2	3	4	5
Capture cost						
Transportation cost						
Sequestration cost						
Capture energy consumption						
Transportation energy consumption						
Sequestration energy consumption						
Traffic conditions						
Contribution to CO_2 emission reduction						
Impact to local water resources						
Difficulty level in deploying the projects						

Notice: mark an 'X' in the box. 0-very low, 1-low, 2-middle, 3-high, 4=very high, 5-extremely high

4.1 CO_2-EOR

EOR through CO_2 flooding (by injection) offers potential economic gain from incremental oil production. EOR is thought to be an important option to mitigate CO_2. Currently, CO_2-EOR technology has gained a lot of engineering experiences. Early in 2006, USA applied many CO_2-EOR projects, and these projects can enhance oil recovery around 234,000 barrels per day [34]. For example, the Oxy company has injected around 1.2×10^9 ft^3/d CO_2 into the Permian basin, recovering oil production around 180,000 barrels per day. The Weyburn is one of the biggest CO_2-EOR projects – this project has operated for many years and is expected to store CO_2 20 Mt and to enhance oil production by around 1.22×10^8 barrels [35]. In China, many enterprises are developing the CO_2-EOR technology. The Sinpec carried out CO_2-EOR experiment in Zhongyuan oilfield in 2006. In 2010, this pioneer project had achieved important results. The 2# plant injected CO_2 around 17,000 tons and water 82,400 m^3, enhancing oil production 3,600 tons [36]. The experiences from these projects have proved the CO_2-EOR to be an applicable technology. In 2009, the CO_2-EOR pilot was applied in Daqing Oilfield [37].

Moreover, when storage is combined with EOR, the benefits of enhanced production can offset some of the capture and storage costs. Typically, the cost of CO_2 injection into an oilfield is around 0.6-8.3US$/t (including the monitoring cost) [29]. But the onshore EOR operations can produce net benefit in the range of 10–16 US$ per ton of CO_2 (the benefit depends very much on oil prices, these figures are based on the oil price in 2003) [29]. The economic benefits from enhanced production make EOR potential early cost-effective options for geological storage.

4.2 CO_2-ECBM

If CO_2 is injected into coal seams, it can displace methane, thereby enhancing CBM recovery. Carbon dioxide has been injected successfully at the Allison Project and in the Alberta Basin, Canada [38]. CO_2-ECBM has the potential to increase the amount of produced methane to nearly 90% of the gas, compared to conventional recovery of only 50% by reservoir-pressure depletion alone [39].

The CO_2 injection of Allison Unit CO_2-ECBM Recovery Pilot Project operations for ECBM recovery commenced in April 1995. The pilot consists of 16 methane production wells, four CO_2 injection wells, and one pressure observation well [29]. A total of 181 million m^3 (6.4 Bcf) of natural CO_2 was injected into the reservoir over six years, of which 45 million m^3 (1.6 Bcf) is forecast to be ultimately produced back, resulting in a net storage volume of 277,000 tCO_2 [29]. In recent years, many CO_2-ECBM projects for evaluating the CO_2 storage capacity, risks and etc. have been supported by NSFC, MOST and NDRC.

When storage is combined ECBM, the benefits of enhanced production can offset some of the capture and storage costs. The economic benefits from enhanced production make ECBM potential early cost-effective options for geological storage.

5. Outlook for EOR and other utilisation options in China and Shaanxi Province

5.1 Oil reserves

EOR sites in Shaanxi Province are mainly Yanchang Oilfield and Changqing Oilfield.

Yanchang Oilfield locates at Yan'an (Yan'an, Yulin, Inner Mongolia included), Shaanxi Province. It starts to produce oil with indigenous method in 1905 (the first onshore oil well in China-Yan No.1 Well, was 80 metres deep and produced 1–1.5 tons oil per day. It drilled well from 5 June to 6 September 1907 with purchased Japanese Dayton drill rig, hiring Japanese technicians and seven workmen). Yanchang Oilfield produced 6,115 tons raw oil until 1948. In 1949 it produced 802 tons raw oil and 176 tons gasoline, which supported the People's Liberation Army marching into the Northwest. Yanchang Oilfield deployed more exploration and construction project after liberation. Its raw oil production reached 150,000 tons in 1985. Till 1998 it already had 10 well-drilling companies, producing 1.7522 million tons raw oil per year. After reshuffle in 2005, its raw oil production grew even more rapidly. In 2007 its production exceeded 10 million tons and in 2009 its production reached 11.2 million tons.

The Changqing Oilfield exploration area is mainly located in the Shaanxi-Gansu-Ningxia basin with an area of about 370,000 km^2. In recent years, oil reserves in Changqing Oilfield have maintained robust growth laying the basis for the promotion of raw oil production. Changqing Oilfield has proven geological oil reserves of about 335.79 million tons, controlled reserves of about 394.04 million tons and prognostic reserves of about 532.75 million tons since 1999. The four main oilfields of Changqing are Shanbei Ansai, Jing'an, Suijing and Wuqi.

5.2 EOR potential

CO_2-EOR is an important technology in CCUS, it can both reduce the emission of greenhouse gases and promote the production of oil, thus will make some benefits.

From around the globe, the potential of CO_2-EOR is about 1600×10^8-3000×10^8 barrels, which is about 15% of the EOR production in the world. Most of the CO_2-EOR projects are in the USA.

In 2008, EOR production in the world was 186.1×10^4 barrels/day; CO_2-EOR production was 27.25×10^4 barrels/day, takes 15.1% of the total EOR production. That is far less than steam-EOR production, which is widely used in oilfields. But as the development of CO_2-EOR, it will replace steam-EOR gradually. For instance, the USA has realised the industrial application of CO_2-EOR, In 2008, 105 CO_2-EOR projects were built with a production of 25×10^4 barrels/day and 80% of them was from Permian basin. That is 38% of the total EOR production and 91% of the CO_2-EOR production in the world. In addition, the number of CO_2-EOR projects in the USA is 85% of the world.

In 2006, China's national Ministry of Science and Technology approved 'greenhouse gas-EOR resource utilisation and underground storage' supported by 'National Key Basic Research Development Plan'. In 2007, China National Petroleum Corporation (CNPC) settled a major science and technology project 'greenhouse gas CO_2 resource utilisation and underground storage'. Also in 2007, CNPC settled a major pilot test 'Jilin Oilfield CO_2-EOR and CO_2 underground storage pilot test'. Thanks in part to this, CO_2-EOR and CO_2 underground storage research has come into a new stage.

In China, gas fields fit for CO_2 storage have reserves of 35×10^8 tons and increased recoverable reserves reaches 3.5×10^8 tons, which is about an 11×10^8 tons oilfield. Domestic research has built CO_2 storage evaluation system and basic theories fit for China's geological features. They have also deployed CO_2-EOR, cost-effective CO_2 capture, CO_2 transport, corrosion and scaling researches. Meanwhile, PetroChina carried out a CO_2-EOR and storage pilot test. From these important achievements in CO_2-EOR and storage, we can see the giant potential in CO_2-EOR.

5.3 CO_2 storage capacity

Sequestrating CO_2 in depleted oil and gas field due to the exploiting of oil and gas makes room for storing CO_2. Assume that all the room which was filled by minable oil and gas underground can be replaced by CO_2, then the CO_2 capacity in oil or gas field can be calculated by the equation below:

$$V_{CO_2} = (V_{oil(stp)}/1000)\times B_0 \times \rho_{CO_2}$$

$$V_{CO_2} = V_{oil(stp)} \times B_g \times \rho_{CO_2}$$

In the equation, VCO_2 is the CO_2 capacity, Mt; Voil(stp) is the volume of minable oil in standard condition; Vgas(std) is the volume of minable gas in standard condition; Bo is the reservoir volume coefficient, non-dimensional; Bg is the gas volume coefficient, non-dimensional; ρ_{CO2} is the density of CO_2 in reservoir conditions.

Hendriks and Bachu [40, 41] estimated the potential CO_2 sequestration volume around the world, depleted oil and gas field in China has a CO_2 capacity of 10 billion tons at most.

6. Conclusions

CO_2 sources fit for CCS demos in Shaanxi Province are mainly methanol, dimethyl ether, synthesis ammonia plants which have high-concentration CO_2 emissions. As these CO_2 emissions cost relatively less to capture and they don’t need too much pre-treatment before transport, it’s an ideal choice to deploy early CCS demos in these industries. CO_2 sources mainly locate at heavy chemical industry bases in Yulin, north Shaanxi and Weinan, south Shaanxi. Yulin District has abundant coal and natural gas resources; it’s an ideal site for CO_2 geological storage where CO_2-ECBM can be deployed. Yan’an District also has many high-concentrated CO_2 sources. Some of these sources are owned by Yanchang and/or Changqing Oilfield; we can use them for CO_2-EOR directly. In a word, as China’s heavy chemical industry bases, Shaanxi Province has abundant CO_2 sources; and its CO_2 storage potential is also huge. All these factors make it convenient for early CCS demonstrations.

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Appendix I:
Oil & Gas plants in Shaanxi Province

Plant name	Plant type	Location	Scale
Attatched to Yanchang Petroleum			
Yanchang Petroleum Zichang oil exploitation plant	Oil exploitation	Yanan Zichang country	Oil production ~400,000t/year in 2006
Yanchang Petroleum Dingbian oil exploitation plant	Oil exploitation	Yulin Dingbian Country	Oil production ~900,000t/year in 2007
Yanchang Petroleum Jingbian oil exploitation plant	Oil exploitation	Yulin Jingbian Country	Oil production ~780,000t/year in 2009
Yanchang Petroleum Wuqi oil exploitation plant	Oil exploitation	Yanan Baotao district	Oil production ~1400,000t/year
Yanchang Petroleum Wangjiachuan oil exploitation plant	Oil exploitation	Yanan Yanchang country	Oil production ~460,000t/year in 2008
Yanchang Petroleum Ganguyi oil exploitation plant	Oil exploitation	Yanan Baotao district	Oil production ~260,000t/year in 2008
Yanchang Petroleum Yongning oil exploitation plant	Oil exploitation	Yanan Zhidan country	Oil production ~1260,000t/year in 2008
Yanchang Petroleum Xiqu oil exploitation plant	Oil exploitation	Yanan Zhidan country	Oil production ~1000,000t/year
Yanchang Petroleum Xingxichuan oil exploitation plant	Oil exploitation	Yanan Ansai country	Oil production ~650,000t/year
Yanchang Petroleum Nanniwan oil exploitation plant	Oil exploitation	Yanan Baotao district	Oil production ~500,000t/year
Yanchang Petroleum Chuankou oil exploitation plant	Oil exploitation	Yanan Baotao district	Oil production ~500,000t/year
Yanchang Petroleum Xiasiwan oil exploitation plant	Oil exploitation	Yanan Ganquan country	Oil production ~420,000t/year
Yanchang Petroleum	Oil exploitation	Yanan Zichang	Oil production

Wayaobao oil exploitation plant		country	~350,000t/year
Yanchang Petroleum Qilicun oil exploitation plant	Oil exploitation	Yanan Yanchang country	Oil production ~300,000t/year
Yanchang Petroleum Zibei oil exploitation plant	Oil exploitation	Yanan Zichang country	Oil production -
Yanchang Petroleum Hengshan oil exploitation plant	Oil exploitation	Yanan Hengshan country	Oil production ~140,000t/year
Yanchang Petroleum Qingpingchuan oil exploitation plant	Oil exploitation	Yanan Yanchuan country	Oil production ~100,000t/year
Yanchang Petroleum Panlong oil exploitation plant	Oil exploitation	Yanan Baota district	Oil production ~140,000t/year
Yanchang Petroleum Zhiluo oil exploitation plant	Oil exploitation	Yanan Fu country	Oil production ~70,000t/year
Yanchang Petroleum Nanqu oil exploitation plant	Oil exploitation	-	Oil production ~120,000t/year
Yanchang Petroleum Zizhou oil exploitation plant	Oil exploitation	Yulin Zizhou country	Oil production ~40,000t/year
Yanchang Petroleum Yingwang oil exploitation plant	Oil exploitation	Yanan Yichuan country	-
Attatched to Changqing Petroleum			
Changqing Petroleum 3th oil exploitation plant	Oil exploitation	Yanan Wuqi country	
Changqing Petroleum 4th oil exploitation plant	Oil exploitation	Yulin Changqing industry base	
Changqing Petroleum 6th oil exploitation plant	Oil exploitation	Yulin Dingbian country	

Identification, Analysis and Mapping of CCUS Target Projects

Supporting early Carbon Capture Utilisation and Storage development in non-power industrial sectors

1. Introduction

1.1 Objective of the report

Carbon Capture and Storage (CCS) is a key technology to reduce China's carbon emissions, while satisfying its increasing demand for electricity and chemical products, and its continuous reliance on coal. However, barriers to demonstration and cost-effective development of fully integrated CCS projects in selected industries include (1) the identification of potentially cost-effective early opportunities and (2) a lack of government facilitation between capture and storage industries to ensure optimal cost-effectiveness. Continued lack of such coordination through industrial policy, regulations and incentive policies will result in prohibitively high cost of initial CCS demonstration projects and is likely to delay further development of potentially cost-effective CCS projects in China.

Preliminary work on CCS in China has focused on CCS in the power sector. However, capture in the power sector is technically challenging, energy-intensive and expensive. Capture can be done at lower cost at large point sources of concentrated CO_2, such as in fertiliser plants, coal-to-liquids facilities and refineries. China has a large industrial base in these sectors, resulting in a significant CO_2 emission reduction potential through CCS.

In recent years China has seen the development of Enhanced Oil Recovery (EOR) activities. EOR injects CO_2 in oil reservoirs to enhance production and prolong the life of the reservoir. EOR is widely applied in the United States and Canada and is in development in the Middle East. China has a large EOR potential and an EOR industry is emerging. CO_2 from nearby high-concentration point sources has a value for EOR operations. This value can be used to develop early cost-effective CCS projects involving industries where capture cost are relatively low.

To date a number of separate preliminary pilots for the capture and storage of CO_2 have been and are being undertaken in China. However, none of these pilots succeed in cost-effectively establishing a fully integrated CCS chain, due to insufficient coordination between capture and storage sectors.

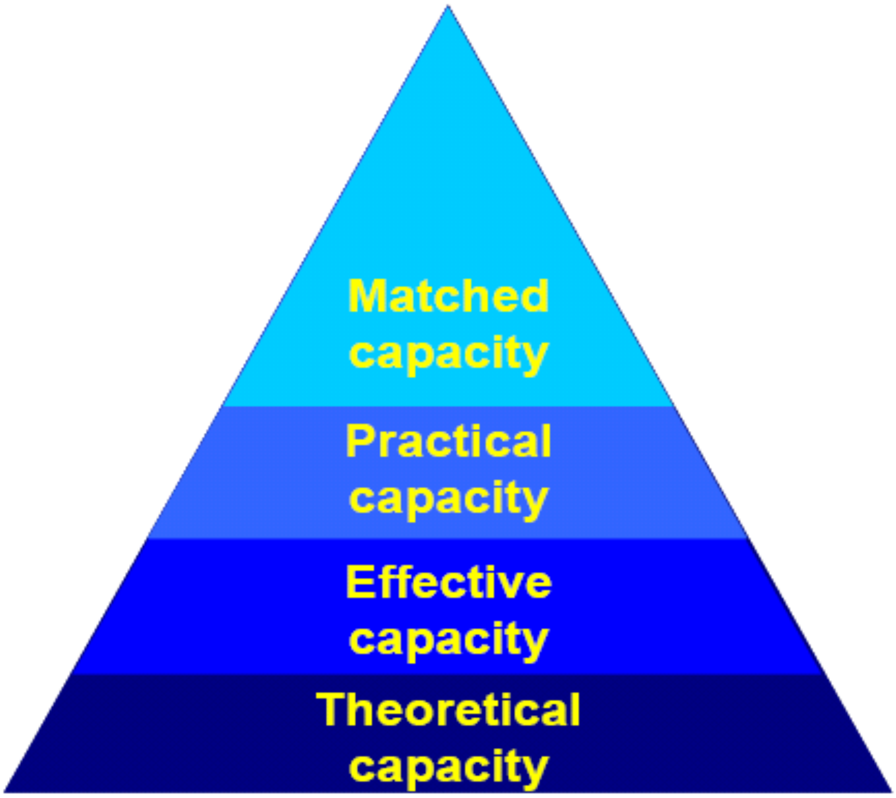
Early demonstration of cost-effective CCS potential in selected sectors can significantly advance CCS development in China in selected industries, in time crossing over into other sectors, including power, as the technology and policy conditions mature.

By directly engaging stakeholders from relevant industries and the EOR sector, the project will explore carbon capture potential and the cost in these industries, and help NDRC and MOST identifying and better coordinating potential CCS early stage demonstration projects, while building awareness in these industries about potential opportunities for collaboration in CCS.

1.2 Methodology and project selecting criteria

To identify the potential CCS project in Shaanxi Province, we set a series of criteria. The following factors need to considered when determining CCS demonstration project: the source-sink matching, the technological feasibility, economical, energy penalty character, policy factor, environment factor, transportation factor, public society factor, safety factor, demonstration effect, the and coordination operation difficulty of the project and so on.

First, the most important factor in the selection of CCS demonstration project is whether the storage **scale matches with the source scale**. It is better to choose single CO_2 emission source, and make sure this single source scale match well with the storage scale. In this way, the collection and transportation cost caused by multi emission source can be avoided.



Second, the technical feasibility should be taken into consideration in every project. To CCS demonstration project, it includes the maturity of CO2 capture technology, transportation and sequestration technologies. For example, EOR is relatively more mature than other sequestration options and significant operational experience has been accumulated in this field. Though less mature, saltwater layer sequestration and coal bed methane mining should also be considered for demonstration.

Third, the cost should be minimised to enhance the economic demonstration effect. In the capture link, high purity CO2 sources should be selected to reduce the capture cost. The transportation should within the economic scope. For sequestration, EOR and ECBM which can bring extra benefits (oil and coal bed gas) should be given priority. Fourth, besides the benefit factor, energy penalty factor is also of great importance. Too high energy penalty will increase the energy consumption and lead to the rise of fuel/raw material price. What's more, it is adverse to the effect of CCS demonstration. So choosing the high purity CO2 sources with little impurity can reduce the CO2 capture cost, which meets the energy saving demands and achieve favourable emission reduction effect.

Fifth, with the increasing awareness of environment protection, the potential effect on the local environment of the CCS demonstration project should be taken into account. For example, the sequestrated CO2 may have impact on local water resources. And the water demand of CCS project may aggravate the local water shortage.

Sixth, some social factors such as transportation, policy, safety and public support should also be paid attention. In terms of transportation, the local terrain, the difficulty of pipe laying and the transportation distance are factors that need to be considered. In terms of policy, the local policy-makers' attitude toward CCS is important. In terms of security, the main factors are the pipeline corrosion and the leakage of CO2 in the transportation process.

Seventh, the demonstration effect of CCS project and the public acceptance for CCS need to be considered. Favourable demonstration effect could only be achieved with the proper selection of location, industry and scale of demonstration, because it is closely related to these factors. The public may worry about the security (e.g. leakage and explosion) of CCS because they do not know much about CCS. Therefore, the public acceptance is one of the considerations, and it can be increased by propaganda and promotion.

Eighth, the difficulty level of coordinating each chain in CCS demonstration project should be considered in the selection of potential project, because many organizations and enterprises in different industries may be involved, such as power plant, chemical plant and oil companies. In conclusion, the selection principles of CCS demonstration project are summarized in Table 1.

Table 1 Selection criteria for choosing CCUS demonstration projects

	Technical feasibility	Match of source and sink	Economic factor	Energy penalty character	Environmental factor	Transportation factor	Policy factor	Social factor	Security factor	Demonstration effect
1.	Technical maturity	CO_2 amount of sources	Capture cost	Capture energy penalty	Contribution of carbon emission reduction	Transportation equipment	Local policy for CCS	Public acceptance degree	CO_2 transportation security	Demonstration site
2.		Sequestration method and amount	Transportation cost	Transportation energy penalty	Impact on local water resources	Terrain			CO_2 leakage	Demonstration scale
3.		Match of emission and sequestration	Sequestration cost	Sequestration energy penalty	Impact on the emission amount of particles	Transportation distance				
4.					Other impact on environment					

*The highlighted are necessary factors.

All the factors are divided into necessary and unnecessary factors. The necessary factors must be satisfied with a priority and are highlighted in Table 1.1. However, for the unnecessary factors, we develop a scoring mechanism to evaluate these factors. For the unnecessary but important factors, such as cost and energy penalty, we can mark a high score/high weight. For those unnecessary but less important factors, such as demonstration, we can give low marks.

Table 1.2: Scoring mechanism for unnecessary factors in choosing CCUS demonstration projects

	0	1	2	3	4	5
Capture cost						
Transportation cost						
Sequestration cost						
Capture energy consumption						
Transportation energy consumption						
Sequestration energy consumption						
Traffic conditions						
Contribution to CO_2 emission reduction						
Impact to local water resources						
Difficulty level in deploying the projects						

Notice: mark an 'X' in the box. 0-very low, 1-low, 2-middle, 3-high, 4-very high,5-extremely high

2 High-purity CO_2 sources in Shaanxi

2.1 Overview of potential CO_2 sources

According to the survey of CO_2 sources in non-power industries of Shaanxi, this section will give a detailed introduction of some typical and representative high purity CO_2 sources, including emission scale, purity, factory type and so on, to provide some references for the selection of CO_2 sources in the CCUS demonstration project.

Ammonia synthesis plants

1) **Shaanxi Heimao Coaking Stock. Co. Ltd.,** located in Hancheng City, is a recycling economy enterprise involving sectors of coke, power generation, chemical industry and construction material. The company set up six projects, one of which is a co-production of ammonia with methanol project with an output of 100,000 t/y (this project belongs to its subsidiary company Heimao Energy Utilization Co. Ltd.). Its

synthesis of ammonia production is about 90,000 t/y, and the byproduct methanol production is about 10,000 t/y. About 380,000 tons of $CO_2$with the purity of 99% is generated in this plant every year.

2) **Shaanxi Qinling Fertilizer Company**, located in Baoji city, has synthesis ammonia production capacity of 160,000 t/y. About 600,000 t/y of CO2 with a purity of 99% is generated in this plant.

3) **Shaanxi Weihe Coal Chemical Industry Group Co. Ltd**., located in Weinan city, has the synthesis ammonia production of 300,000 t/y and the urea production of 520,000 t/y with bituminous coal as a raw material. About 1,140,000 t/y of CO_2 with a purity of 99% is generated in this plant.

4) **Shaanxi Chenghua Co. Ltd.,** located in Chenggu county, Hanzhong city, is the only enterprise which has urea production and waste heat driven power generation projects in Southern Shaanxi Province. It has synthesis ammonia production of 120,000 t/y, urea production of 140,000 t/y and ammonium bicarbonate production of 60,000 t/y. About 450,000 t/y of CO_2 with a purity of 99% is generated in this plant.

5) **Shaanxi Coal and Chemical Industry Group Co. Ltd**., located in the fine chemical park of Hua county, Weinan city, has synthesis ammonia output of 260,000 t/y, the urea output of 320,000 t/y, the ammonium phosphate output of 260,000 t/y and the three elements compound fertiliser output of 100,000 t/y. In addition, the technical improvement project for energy conservation and emission reduction contracted by Shaanxi Coal and Chemcial Industry Group Co. Ltd. has started total construction in October 2008, and was put into operation in November 2011. This project has synthesis ammonia output of 300,000 t/y and urea output of 940,000 t/y. About 2,280,000 t/y of CO_2 with a purity of 99% is generated in this plant.

6) **Yanchang Petroleum Xinghua Large Chemical Industry Project**, owned by Shaanxi Yanchang Petroleum (Group) Co. Ltd. and located in Xingping City, was put into operation on 28 December 2011. It includes synthesis ammonia output of 300,000 t/y, methanol output of 300,000 t/y, soda output of 300,000 t/y and ammonium chloride output of 324,000 t/y. This is an integrated system with ammonia, alcohol and alkali outputs. In the system, the waste gases of CO and CO_2 in the ammonia synthesis process can be used for methanol synthesis, and the purge gas in the methanol synthesis process can be used for ammonia synthesis. This can reduce the green gas emissions and there are no sulphurous pollutants discharged in the process. About 1,140,000 t/y of CO_2 with a purity of 99% is generated in this plant.

7) **Shaanxi Fangyuan Chemical Industry (Group) Co., Ltd**., located in Yuyang district, Yulin City, operates a synthetic ammonia production line by adopting the

water coal slurry gasification technology, KELLOGG natural gas MEDP steam conversion technology and residual vaporisation technology. Synthetic ammonia output is 300,000 t/y, among which 180,000 t/y is used for urea production and the remaining 120,000 t/y together with the by-product are used for soda production. About 1,140,000 t/y of CO_2 with a purity of 99% is generated at this plant.

Methanol plants

8) The 1,800,000 t/y methanol project in **Huangling County, Yan'an City**, has been approved and will be co-constructed by the People's Government of Yan'an city, Shaanxi Yanchang Petroleum (Group) Co. Ltd. and the Hong Kong and China Gas Company Ltd. With coal, gas and oil as raw materials, this project has a methanol output of 1,800,000 t/y, MTO (methanol-to-olefin) output of 600,000 t/y, light oil reforming capacity of 400,000 t/y, polyethylene output of 450,000 t/y, polypropylene output of 250,000 t/y, butanol-octanol output of 200,000 t/y, and ethylene propylene rubber output of 60,000 t/y. About 4,500,000 t/y of CO_2 with a purity of 99% is generated in this plant.

9) The 1,800,000 t/y methanol production and deep processing project in **Fu County, Yan'an City**, was constructed and is operated by Yanchang Petroleum Yan'an Energy Chemical Industry Co. Ltd., which is one of the subsidiary enterprises of Shaanxi Yanchang Petroleum (Group) Co. Ltd. About 6,800,000 t/y of CO2 with a purity of 99% is generated in this plant.

10) The 1,800,000 t/y coal to methanol project in **Jingbian County, Yan'an City**, is in the charge of Shaanxi Yanchang China Coal Yulin Energy Chemical Industry Co. Ltd.; a large scale chemical enterprise making comprehensive utilisation of coal, gas, oil and salt which was jointly established by Shaanxi Yanchang Petroleum (Group) Co. Ltd. and China National Coal Group Co. Ltd. It is responsible for the construction of the start-up projects in the Jingbian industrial zone of the comprehensive utilisation of energy engineering and chemical industries, which is 10km away from the northeast of Jingbian County. This industrial zone has total methanol output of 1,800,000 t/y. This project is planned to be put into operation in 2014, and the expected CO_2 emission is 6,800,000 t/y with 99% purity.

11) The 1,700,000 t/y methanol project in **Yuheng industrial zone of Yulin City,** is undertaken by Shaanxi Yanchang Petroleum Yulin Coal Chemical Company, a wholly owned subsidiary of Shaanxi Yanchang Petroleum (Group) Co. Ltd. The company owned the acetic acid project with output of 1,000,000 t/y and is the key project of its kind in Shaanxi. The first stage project has methanol output of 200,000 t/y and acetic acid output of 200,000 t/y. The second stage has methanol output of 1,500,000 t/y,

acetic acid output of 400,000 t/y, vinyl acetate output of 300,000 t/y, acetic anhydride output of 200,000 t/y and acetate fibre output of 100,000 t/y. The CO_2 emissions are expected to be 6,400,000 t/y with purity of 99%.

12) The 600,000 t/y methanol project in **Weicheng County, Xianyang City**, is undertaken by Shaanxi Xianyang Chemical Industry Co. Ltd., a wholly owned subsidiary of Shaanxi Investment Group Co. Ltd. It has a coal to methanol output of 600,000 t/y and a power generation capability of 25 MW. The CO_2 emissions are about 5,700,000 t/y.

13) The gas to methanol/dimethyl ether project in **Yanchang County, Yan'an City**, belongs to Shaanxi Yanchang Petroleum (Group) Co. Ltd. and the People's Government of Yan'an City. The methanol output of the first stage is 600,000 t/y. The second stage is designed to produce dimethyl ether directly from syngas, with the output of 700,000 t/y and is in the phase of inviting investment. The CO_2 emissions are expected to be 3,250,000 t/y after the project is established.

14) The coal to methanol project of **Shaanxi Shenmu Chemical Industry Co**., located in the industrial development zone of Shenmu County, Yulin City. The designed methanol output is 600,000 t/y. The first stage with output of 200,000 t/y has already been put into production. The CO_2 emissions are expected to be 1,500,000 t/y.

15) The coal to methanol project of **Yanzhou Coal Yulin Energy Chemical Industry**, located in the Caojiatan Town, Yuyang County, Shaanxi Province. The designed methanol output is 2,300,000 t/y, and the present output is 600,000 t/y during the first stage. The CO_2 emissions are 7,250,000 t/y.

16) The coal to methanol project in the economic development zone of **Yulin City** has a methanol output of 600,000 t/y and the CO_2 emissions are 1,500,000 t/y.

17) The methanol plant of **Changqing Oilfield**, located in Yulin City, belongs to Changqing Branch of China National Petroleum Corporation. The methanol output is about 100,000 t/y. The CO_2 emissions are about 250,000 t/y with purity of 99%.

Hydrogen plant

18) The 90,000 Nm3/h hydrogen project of **Shaanxi Shenmutianyuan Chemical Industry Co. Ltd.**, located in Shenmu County, Yulin City, produces hydrogen from coal. The CO_2 emissions are about 400,000 t/y with purity of 99%. (www.huaxigas.com/gsyj_js.asp)

Ethanol plant

19) **Shaanxi Baoji Alcohol Plant**, located in Baoji City, is a large scale light industry enterprise which produces 350,000 tons of beer and 30,000 tons of alcohol every year. Its main products include superior alcohol and edible alcohol with the brand of 'Tangqingchencang', and various types of beer with the brand of 'Baoji'. The CO_2 emission amount is about 30,000 t/y.

Dimethyl ether plants

20) The 1,000,000 t/y dimethyl ether project in **Pucheng County** was constructed by Shaanxi Coal and Chemical Industry Group Co. Ltd. It adopts advanced pressurised gasification technology for coal-water slurry with coal as the raw material. The outputs of methanol and dimethyl ether are about 1,500,000 and 1,000,000 t/y, respectively. The expected annual CO_2 emissions are about 6,000,000 tons.

21) The 1,000,000 t/y dimethyl ether project in **Xianyang City**, was in the charge of Shaanxi Carbonification Energy Co. Ltd. The dimethyl ether outputs of the first and second stages are about 400,000 and 600,000 t/y, respectively. The construction will be completed in 2013. The expected CO_2 emissions amount are about 2,500,000 t/y.

22) The 1,000,000 t/y dimethyl ether project in **Yulin City**, was in the charge of Shenfu economic development zone and is located in the Jinjie industrial park in Shenmu County. The expected annual CO_2 emissions are about 2,500,000 tons.

The characteristics of CO_2 sources directly affect the cost and energy penalty of CO_2 capture, and exert a great influence on the cost and energy penalty of the whole demonstration project. Therefore, it is of key importance to select suitable CO_2 sources for the demonstration project. The most important factors that influent the demonstration project are the technical feasibility, cost and energy penalty, so the following two key principles must be taken into consideration when selecting CO_2 sources.

1) **Technical feasibility and maturity principle.** This means that the capture technology is achievable in engineering, and the mature technology should be given priority to reduce the risk and uncertainty of the project.

2) **The energy penalty and cost minimisation principle.** To get an effective demonstration, it is necessary to minimise the cost budget and energy penalty of the CCS. For the EOR technology, the benefits brought by the increase of oil exploitation should not be less than the cost of capture and transportation. According to a survey, the acceptable price of CO_2 for petroleum enterprise is 20$/t, so these enterprises can only make balance or profit when the cost of capture and transportation is less than 20$/t.

Based on the above criteria, the selected proper CO_2 sources for CCS demonstration project are shown in Table 2.1.

Table 2.1: CO_2 sources suitable for demonstration project.

No.	Plant Name	Location	Plant type	Emission scale	CO_2 purity	Policy support
1.	Yuheng industry zone	Yulin	Methanol	6400000t/y	High	YES
2.	Jingbian	Yanan	Methanol	6800000t/y	High	YES
3.	Huangling	Yanan	Methanol	4500000t/y	High	YES
4.	Yanchang	Yanan	Methanol/DME	3250000t/y	High	YES
5.	Shenmu	Yulin	Methanol	1500000t/y	High	YES
6.	Changqing	Yulin	Methanol	250000t/y	High	YES
7.	Shenfu	Yulin	DME	2500000t/y	High	YES
8.	Fangyuan Yuyang	Yulin	Ammonia	1140000t/y	High	YES
9.	Yanchang Petroleum	Xingping	Ammonia	1140000t/y	High	YES

3. EOR potential in Shaanxi

3.1 Characterisation of potential EOR sites

In 2006, China's national Ministry of Science and Technology approved 'greenhouse gas-EOR resource utilisation and underground storage' supported by 'National Key Basic Research Development Plan'. In 2007, China National Petroleum Corporation (CNPC) settled a major science and technology project 'greenhouse gas CO_2 resource utilisation and underground storage'. Also in 2007, CNPC settled a major pilot test 'Jilin Oilfield CO_2-EOR and CO_2 underground storage pilot test'. Thanks in part to this, CO_2-EOR and CO_2 underground storage research has come into a new stage.

In China, gas fields fit for CO_2 storage have reserves of 35×10^8 tons and increased recoverable reserves reaches 3.5×10^8 tons, which is about an 11×10^8 tons oilfield. Domestic research has built CO_2 storage evaluation system and basic theories fit for China's geological features. They have also deployed CO_2-EOR, cost-effective CO_2 capture, CO_2 transport, corrosion and scaling researches. Meanwhile, PetroChina carried out a CO_2-EOR and storage pilot test. From these important achievements in CO_2-EOR and storage, we can see the giant potential in CO_2-EOR.
The main EOR sites in Shaanxi Province are the Yanchang Oilfield and Changqing Oilfield.

Yanchang Oilfield locates at Yan'an (Yan'an, Yulin, Inner Mongolia included), Shaanxi Province. It starts to produce oil with indigenous method in 1905 (the first onshore oil well in China-Yan No.1 Well, was 80 metres deep and produced 1–1.5 tons oil per day. It drilled well from 5 June to 6 September 1907 with purchased Japanese Dayton drill rig, hiring Japanese technicians and seven workmen). Yanchang Oilfield produced 6,115 tons raw oil until 1948. In 1949 it produced 802 tons raw oil and 176 tons gasoline, which supported the People's Liberation Army marching into the Northwest. Yanchang Oilfield deployed more exploration and construction project after liberation. Its raw oil production reached 150,000 tons in 1985. Till 1998 it already had 10 well-drilling companies, producing 1.7522 million tons raw oil per year. After reshuffle in 2005, its raw oil production grew even more rapidly. In 2007 its production exceeded 10 million tons and in 2009 its production reached 11.2 million tons.

The Changqing Oilfield exploration area is mainly located in the Shaanxi-Gansu-Ningxia basin with an area of about 370,000 km^2. In recent years, oil reserves in Changqing Oilfield have maintained robust growth laying the basis for the promotion of raw oil production. Changqing Oilfield has proven geological oil reserves of about 335.79 million tons, controlled reserves of about 394.04 million tons and prognostic reserves of about 532.75 million tons since 1999. The four main oilfields of Changqing are Shanbei Ansai, Jing'an, Suijing and Wuqi.

Table 2.2 Inventory of oil field in Shaanxi

Plant name	**Plant type**	**Location**	**Scale**
Attached to Yanchang Petroleum			
Yanchang Petroleum Zichang oil exploitation plant	Oil exploitation	Yanan Zichang country	Oil production ~400,000t/year in 2006
Yanchang Petroleum Dingbian oil exploitation plant	Oil exploitation	Yulin Dingbian Country	Oil production ~900,000t/year in 2007
Yanchang Petroleum Jingbian oil exploitation plant	Oil exploitation	Yulin Jingbian Country	Oil production ~780,000t/year in 2009
Yanchang Petroleum Wuqi oil exploitation plant	Oil exploitation	Yanan Baotao district	Oil production ~1400,000t/year
Yanchang Petroleum Wangjiachuan oil exploitation plant	Oil exploitation	Yanan Yanchang country	Oil production ~460,000t/year in 2008
Yanchang Petroleum Ganguyi oil exploitation plant	Oil exploitation	Yanan Baotao district	Oil production ~260,000t/year in 2008
Yanchang Petroleum Yongning oil exploitation plant	Oil exploitation	Yanan Zhidan country	Oil production ~1260,000t/year in 2008
Yanchang Petroleum Xiqu oil exploitation plant	Oil exploitation	Yanan Zhidan country	Oil production ~1000,000t/year
Yanchang Petroleum Xingxichuan oil exploitation plant	Oil exploitation	Yanan Ansai country	Oil production ~650,000t/year
Yanchang Petroleum Nanniwan oil exploitation plant	Oil exploitation	Yanan Baotao district	Oil production ~500,000t/year
Yanchang Petroleum Chuankou oil exploitation plant	Oil exploitation	Yanan Baotao district	Oil production ~500,000t/year
Yanchang Petroleum Xiasiwan oil exploitation plant	Oil exploitation	Yanan Ganquan country	Oil production ~420,000t/year

Yanchang Petroleum Wayaobao oil exploitation plant	Oil exploitation	Yanan Zichang country	Oil production ~350,000t/year
Yanchang Petroleum Qilicun oil exploitation plant	Oil exploitation	Yanan Yanchang country	Oil production ~300,000t/year
Yanchang Petroleum Zibei oil exploitation plant	Oil exploitation	Yanan Zichang country	Oil production -
Yanchang Petroleum Hengshan oil exploitation plant	Oil exploitation	Yanan Hengshan country	Oil production ~140,000t/year
Yanchang Petroleum Qingpingchuan oil exploitation plant	Oil exploitation	Yanan Yanchuan country	Oil production ~100,000t/year
Yanchang Petroleum Panlong oil exploitation plant	Oil exploitation	Yanan Baota district	Oil production ~140,000t/year
Yanchang Petroleum Zhiluo oil exploitation plant	Oil exploitation	Yanan Fu country	Oil production ~70,000t/year
Yanchang Petroleum Nanqu oil exploitation plant	Oil exploitation	-	Oil production ~120,000t/year
Yanchang Petroleum Zizhou oil exploitation plant	Oil exploitation	Yulin Zizhou country	Oil production ~40,000t/year
Yanchang Petroleum Yingwang oil exploitation plant	Oil exploitation	Yanan Yichuan country	-
Attached to Changqing Petroleum			
Changqing Petroleum 3th oil exploitation plant	Oil exploitation	Yanan Wuqi country	
Changqing Petroleum 4th oil exploitation plant	Oil exploitation	Yulin Changqing industry base	
Changqing Petroleum 6th oil exploitation plant	Oil exploitation	Yulin Dingbian country	

delivery temperature should also not be too high, because high temperature would make the cost of heating and insulation increase rapidly, as the Canyon Reef Project requires, the CO_2 transportation temperature does not exceed 48.9°C.

Strict control of content of water and H2S and other acidic components is very necessary, to prevent the emergence of excessive pipelines corrosion in the transport process. Material flow should not contain free water, as well as the content of H2S not exceeding the prescribed value (often 1500ppm). Different ways of terminal handling (for sequestration or for oil), have different requirements of material flow composition. Low nitrogen content flow is very important for EOR, but it is not so important if CO_2 is to be sealed in the brine layer.

- **Rail/ Road**

The liquid CO_2 can be transported by the tank truck with a low temperature adiabatic refrigerated tank. The storage conditions of CO_2 in the tank truck should be considered according to the specific circumstances, which are usually (1.7MPa, -30°C) or (2.08MPa, -18°C). The capacities of the tank are in the range of 2t to 50t. Tailor-made tank is necessary when using railway and its transport pressure is about 2.6MPa.

Tank transport by highway and railway, has the advantages of flexible, adaptable, convenient, reliable and so on, but has much higher cost than pipeline transport. An IPCC report (2005) indicated that this type of transport system is not economical (except for small scale transport) compared to the pipeline transport and ship transport, so it is impossible to be used in large scale CCS system.
It was necessary to state that there is also vaporisation problem in the truck transport process. The vaporised rate depends on the storage time in the truck, and it can reach up to 10%.

- **Ship**

Ship transport of CO_2 may be more attractive from the view of economic feasibility in some cases, especially for long distance transport or cross-sea transport. The large scale transport of LPG (which consists mainly of propane and butane) by seagoing tanker has been commercialised. The feature of liquid CO_2 is similar to that of LPG, so the same method can be adopted for CO_2 transport. However, due to the limited demand for CO_2, the current transport scale is relatively small. If there is demand for this type of system, this technology can be gradually employed in the large scale CO_2 transport ships.

The pressure of CO_2 is usually kept at 0.7MPa when using ship transport. The capacity of the liquid tank and the character of the loading and unloading system are the key factors that determine the total transport cost (IPCC, 2005). ASPELUND et.al.(2006) pointed out that it was the most economical way to transport CO_2 after bring compressed to 6.5 bar and -52ºC. They also pointed out that when the distance was 1500km, the energy consumption rate was 142kWh/tCO_2 and the transport cost was 0.351RMB/t/km. Statoil et.al.(2004) and IEA GHG(2004) pointed out respectively that the transport cost were 42US$/t (7600km) and 35US$/t (7600km).

The comparisons of different transportation method, including economic and preferable scale comparison, are shown in Table 4.1.

Table 4.1: Comparisons of different transportation method

Transportation method	**Preferable scale**	**CO_2 transportation cost**
Pipeline	Large scale, >2Mt/year	~1$/t/100km
Railway/Road tanks	Small scale	6~17$/ t /100km
Ship	Median-large	0.6~5$/ t /100km

4.2 Existing transportation infrastructure and potential physical barriers in Shaanxi

As a major coal-producing province in China, Shaanxi has a developed traffic system. Shaanxi Province has a developed railway network formed of north (Shenshuo), middle (Houxi and Longhai) and south (Xihe, Xikang and Baocheng) transport channels. These channels connect the railway network of northern Shaanxi, Guanzhong and southern Shaanxi. Moreover, construction of Taizhong-Yinchuan railway, Xiyan railway and the Xiping railway and railway extension guarantees the export of energy resources from Shaanxi Province. In pipeline construction, some cities of Shaanxi Province are in the West-East line; thus Shaanxi has some pipeline transport capacity.

Up to the end of 2007, highways in Shaanxi had reached 121,300km, highway density has increased from 26km per hundred square kilometers in 2005 to 58.9km per hundred square kilometers in 2007, which was 21.7% higher than the national average level. Expressway density has reached 1km per square kilometer, 0.44% higher than the national average level. In Shaanxi Province, expressway was 2063km; first and second class highway was 6771km; and three and four class highway was 81995km. 55.9% of them were bituminous or cement roads. Since 2005, Shaanxi has built many expressways, like those connecting Yangxian-Hanzhong-Mianxian, Fuping-Yumenkou, Huangling-Yan'an-Yulin-boundary of Shaanxi and Inner Mongolia, and new mileage was 1012km. In 2007, Shaanxi built five expressways, include Qinling Zhongnanshan tunnel, Huxian-Yangxian, Wubao-Zizhou-Jingbian, Xianyang-Yongshou. New mileage was 418km; total mileage reached 2063km. After the breakthrough of 1000km in 2003, it was the first to exceed 2000km in West China, ranking 10th in the country; eight cities, one district and 65 counties were connected by expressway. Based on the construction of expressway and rural highway, Shaanxi Province also promoted the transformation of national and provincial highways and 219km first class highways and 727km second highways were built in three years, this substantially improved the road conditions and technical level. Also in 2007, national and provincial highways, such as the Guanzhong ring road, G316, S201, S303, etc. as key objects, attracted 1.1 million Yuan and 350km highway was built. The entire construction of Guanzhong ring road pushed forward the development strategy of Guanzhong 'One Line, Two Districts'.

Traffic conditions in Shaanxi Province indicate that Shaanxi has a relatively well-developed railway and highway system, and it can basically meet the need for energy export. Besides, Shaanxi Province is located in the West-gas-to-East pipeline, making it has a certain pipeline capacity, and the terrain conditions are fit for pipeline laying.

4.3 Recommendations on selection of transport options

Considering traffic situation in Shaanxi Province and the feature and cost of different CO_2 transportation methods, we suggest taking railway or tanks to transport CO_2 for small scale CCS demos. As the demos scale reach a high level, for instance if we can sequestrate two mega tons/year CO_2, then the pipeline transportation method can be used.

5. Source-sink matching options

5.1 Description of source-sink matching options according to selection criteria

In consideration of economics, we selected CO2-EOR as our recommended CCUS demonstration. As outlined previously, Shaanxi Province has two oil fields – the Yanchang Oilfield and Changqing Oilfield. Around these two oil fields, the potential CO_2 sources for CCS demonstration project in Shaanxi Province are shown in Figure

5.1. Most of these sources are methanol plants, dimethyl ether plants and ammonia synthesis plants. These plants have high purity CO_2, which leads to low cost and energy penalty for CO_2 capture and needs no pre-treatment before transportation. These sources are suitable for the early CCUS demonstration project. These emission sources are located intensively in heavy chemical industry bases, such as Yulin and Weinan. The Yulin area is abundant in coal and natural gas, and it is also one of the ideal CO_2 sequestration sites. CO2-ECBM or CO2-EOR can be demonstrated in these areas. There are also many high purity CO_2sources in the Yan'an area, and some of these sources are owned by Yanchang Oilfield or Changqing Oilfield. So the CO_2 from sources can be used directly to enhance oil recovery rates. In brief, as one of the national heavy chemical industry bases, Shaanxi Province has a large number of high purity CO_2 sources and large potential for CO_2 sequestration, so it is suitable to apply an early CCUS demonstration project.

Figure 5.1: The applicable CO_2 sources for CCS demonstration.

According to the CCUS project selection criteria, the recommended projects in Shaanxi Province are listed in Table 5.1.

Table 5.1: Recommended non-power CCUS projects in Shaanxi Province

	CO_2 sources	**Transportation method**	**Storage type**	**Storage location**
Case 1	Yanchang oil field methanol plant	Pipeline	EOR	Yanchang Oilfield
Case 2	Yanan Fuxian methanol plant	Pipeline	EOR	Yanchang Oilfield
Case 3	Changqing oil field methanol plant	Highway/railway tanks	EOR	Changqing Oilfield
Case 4	Jingbian methanol plant	Pipeline	EOR	Changqing Oilfield

5.2 Further description of selected source-sink matches

5.2.1 Description of stakeholders involved

Chinese governmental institutions are playing major roles in monitoring, managing, and developing CCS technologies and regulations, while big businesses, like power generation and resource companies, are also key stakeholders. The following are several institutions that are very likely to be involved in the CSS field:

China’s non-power generation development and related climate change issues are coordinated by the State Council, in which the National Leading Committee on Climate Change was established; it is led by Premier Wen Jiabao. Under the State Council, several key government ministries related to climate change issues include the National Development and Reform Commission (NDRC), the Ministry of Science and Technology (MoST), the Ministry of Finance (MoF), the Ministry of Environmental Protection (MEP), the Ministry of Land and Resources (MLR), the State Administration of Work Safety (SAWS) and local governments like Provincial Governments, Autonomous Regions, and Municipalities. Various stakeholders of the ministries are now adopting different roles in policy establishment, project approval, international negotiation, investment and project planning, research and development of CCS technologies, and the environmental issues related to development of clean coal and advanced power generation.

Investment and implementation of CCS related technologies have been carried out by several energy companies, for example power generation groups such as Huaneng and Huadian, the electric grid companies like State Grid Corporation of China, resource companies like PetroChina, Sinopec, and Shenhua group, Yan chang Petroleum and so on.

In consideration of the cooperation among multiple authorities, it is better that the project implementers are those who own the CO_2 sources and oil fileds. Yan Chang Petroleum is recommended as the project construction and operator for case 1 and case 2, and Changqing Petroleum for case 3 and case 4.

5.2.2 Qualitative assessment of economics (more/less expensive than published cost)

Table 5.2 is the preliminary economic evaluation of the indentified CCS projects in Shaanxi Province. Compared with application in power sector, CCS demonstration in non-power sector, especially in chemical industry with high-purity CO_2 emissions, has the advantage of cost reduction. Typically, the CO2 capture cost from PC (coal-pulverised plant) ranges from 35–50$/t, but is only 15–20$/t in a methanol plant. Considering the benefit from oil production, the total CCS cost of the recommended cases shows obvious economic attractions.

Table 5.2: Qualitative assessment economics

	CO_2 capture cost	**Transportation cost**	**Injection cost**[5]	**Total CCS cost**[6]	**Total CCS cost after considering the oil benefit**[7]
Case 1	15~20$/t	1.5$/t[1]	6$/t	22.5~27.5$/t	-50.5~5.5$/t
Case 2	15~20$/t	3$/t[2]	6$/t	24~29$/t	-46~7$/t
Case 3	15~20$/t	8$/t[3]	6$/t	29~34$/t	-41~12$/t
Case 4	15~20$/t	3$/t[4]	6$/t	24~29$/t	-46~7$/t
Capture from power sector	35~50$/t[8]	3$/t[9]	6$/t	44~59$/t	-20~37$/t

1.Pipeline transportation, 150km. 2. Pipeline transportation, 300km. 3. Highway tanks transportation, 100km. 4. Pipeline transportation, 300km. 5. Excluding benefit from enhanced oil, data from IPCC special report on carbon capture and storage. 6. Excluding benefit from enhanced oil. 7. Including the benefit from oil production. Based on IPCC report, the net EOR cost is around -16$/t assuming the oil price is 20$/t. In this report, the oil price is assumed to range from 20$/t to 100$/t. 8. CO2 is captured from traditional coal-fired power plant. 9. Pipeline transportation, 300km.

6. Conclusions

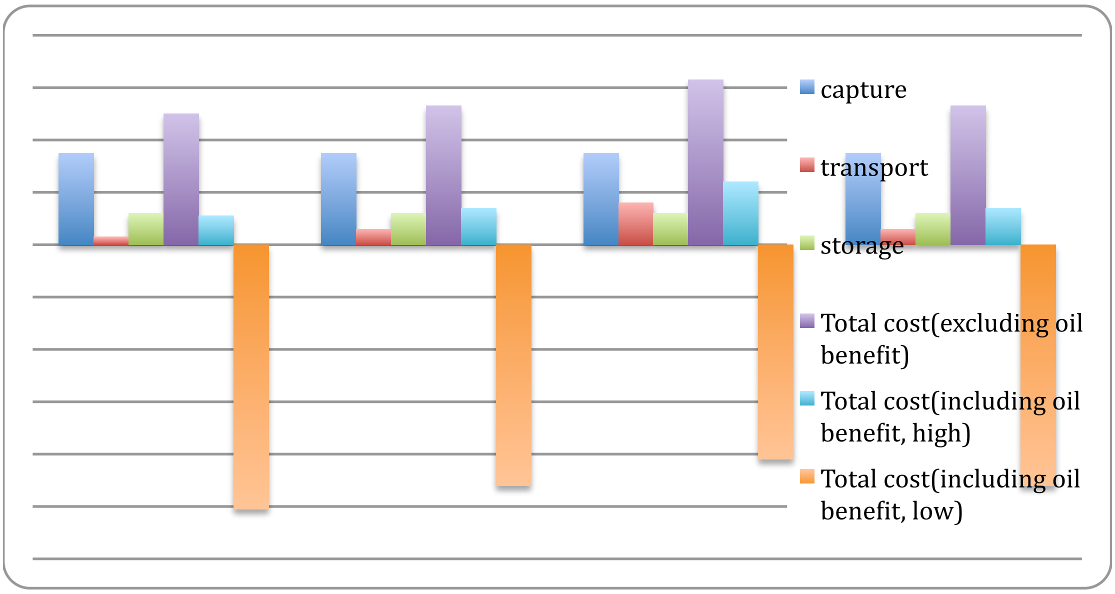
6.1 Total identified potential for cost-effective source-sink matching

In this project, we investigated the high-purity CO_2 sources, the oil reserves, and the early CCUS opportunities in non-power sector in Shaanxi Province. According to our study, Table 6.1 listed our recommended CCUS projects in Shaanxi Province. The cost performance of the four selected cases area summarised in Figure 6.1. All these cases show obvious economic advantages, which indicate that CCUS application in the non-power sector in economically feasible.

Table 6.1 Recommended non-power CCUS projects in Shaanxi province

	CO_2 source type	**Source location**	**Transportation method**	**Storage type**	**Storage location**	**CO_2 injection scale**	**Oil field location**
Case 1	Yanchang oil field methanol plant	Yanan	Pipeline	EOR	Yanchang Oilfield	3.2 million tons/year	Yanan
Case 2	Yanan Fuxian methanol plant	Yanan	Pipeline	EOR	Yanchang Oilfield	6.8 million tons/year	Yanan
Case 3	Changqing oil field methanol plant	Yulin	Highway tanks	EOR	Changqing Oilfield	0.25 million tons/year	Yulin
Case 4	Jingbian methanol plant	Yulin	Pipeline	EOR	Changqing Oilfield	6.8 million tons/year	Yulin

Figure 6.1 Cost performance of the selected cases



6.2 Recommendations

This report has identified 4 cost-effective full-chain CCUS projects based on a matching of high-purity industrial CO2 point sources and EOR potential in Shaanxi. In order to develop these projects we here present our key recommendations:

a. Support further technical and economic feasibility studies on the proposed demonstration projects
b. Encourage discussion among relevant stakeholders on implementation aspects of the proposed demonstration projects
c. Identify key project risks and barriers and develop government measures to mitigate these risks and barriers
d. Provide long-term stable investment conditions and incentives for project participants in capture, transportation and utilization sectors.
e. Select one key demonstration project to focus further effort on.
f. Develop medium-term plan for developing other cost-effective CCUS projects in Shaanxi

Implementing CCS demonstration project. Form a government supported and enterprise mainstay regime to coordinate interests among industries; implement demonstration projects; accelerate the transfer of scientific achievements; and realise the combination of scientific and industrial plans. Use foreign funds to support CCS demonstration projects, and meanwhile make sure that the nation’s fund takes a substantial proportion of the total investment to mitigate the enterprise’s risk and responsibility.

Building CCS technological platform and strengthening international cooperation. Form a national low carbon technology research centre and an alliance between industry, academia and the research community to make CCS key technology breakthroughs. Strengthen international cooperation in low carbon revolution areas, and build an international regime with low carbon technology R&D, competition and optimisation.

The project strongly recommends that (at least) the first demonstration project should be a national programme, conducted by a consortium of complementary partners led by a pioneering company with government support and the learning and experiences gained during demonstration can be accessed among all interested enterprises. Chinese enterprises have started taking actions in CCS research and development. However, there is an absolute necessity for strong government leadership to form a national CCS consortium. A demonstration project should be a horizontally integrated project along the CCS value chain in order to combine strengths and reduce weaknesses substantially. Such integration could be achieved through either signing long-term contract among participating companies in capture, transportation and storage along the CCS value chain or establishing a joint venture among shareholder companies to share risk among different companies.

China has an opportunity to observe and draw lessons from the experiences of other countries in deciding how it wants to proceed in developing regulations. At the same time, it is important to recognise that these regulatory frameworks are being prepared by nations that expect to establish a legal basis for the commercial deployment of CCS. A new set of policy options are needed at the national level to address technical, institutional, legal, regulatory and financial gaps, promote demonstration projects with a standardised approach that provides replicable cases for future projects. Policy options at the national level have important implications not only for CCS at the national level but also for demonstration projects at project level.

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Summary Report: Technical, Financial and Regulatory Assessments of CCUS in Shaanxi Province

Supporting early Carbon Capture Utilisation and Storage development in non-power industrial sectors

1. Background and Introduction

1.1 Status and rationale for CCUS in Shaanxi Province

Shaanxi province in Central Mainland China is a region that has abundant fossil fuel resources of coal, natural gas and crude oil and has been ranked third in China for the production of these resources. The many fossil fuel consuming industries in the province accounted for 138 million tons of CO_2 emissions in 2005, making up 2.4 % of China's total emissions. By 2009, the CO_2 emissions from Shaanxi rose to 209 million tons/year and they may reach 450 million tons/year by 2015. The province is home to numerous coal fired power stations, which account for 70 % of the overall emissions. In addition, there is also a substantial cement production industry, which accounts for 10 % of the CO_2 emissions. The large chemical coal industry (e.g. ammonia and methanol production) in the region accounts for around 20 % of the CO_2 emissions.

In the context of this report, Carbon Capture and Utilisation Storage (CCUS) refers to the matching of industrial high-purity CO_2 sources, such as those of fertiliser plants or coal-to-liquid fuels facilities, with a sink industry which would make beneficial use of the captured and transported CO_2, such as Enhanced Oil Recovery (EOR). The capture of CO_2 from industrial high-purity sources requires much less additional process development than conventional carbon capture from the power generation industries because the production of pure CO_2 is already an inherent part of the process, often arising from gasification technology. Similarly, the sink industries may require less development than conventional CO_2 storage in geological formations like saline aquifers; hence, CCUS does not refer here to conventional carbon capture and storage.

As Shaanxi is home to many high-purity CO_2 source industries and has oilfields operated by Changqing oilfield company and Shaanxi Yanchang Petroleum Group which are believed to be amenable to CO_2-EOR with an estimated vast CO_2 storage capacity, it makes an excellent candidate region for the development of CCUS demonstration projects which could prepare the way for larger scale deployment of CCUS, and eventually conventional CCS from the power generation sector. In addition, the Ordos Coal Basin sites Coal Bed Methane (CBM) extraction that could also potentially benefit from enhanced recovery via CO_2 injection.

Local and national politics is supportive of CCUS activities in Shaanxi. In the report "The 12th five year plan for national economic and social development of Shaanxi Province", a CO_2 emission reduction target of 15% was set for the province over the period 2016-2020 and Shaanxi is envisaged to be China's low carbon demonstration province. Low carbon development is expected to be an important theme of the economy of the province. In 2010, Shaanxi was selected as one of China's low carbon experimental provinces. In the same year, the province came up with "Low-carbon pilot implementation programme in Shaanxi Province". This programme set out the low carbon development roadmap for Shaanxi, with recommendations for adjusting the economic structure, deploying pilot demonstrations, developing low carbon technology and promoting CCUS cooperation with the USA, Holland and other countries. The aim of this programme is to reduce the carbon emissions by 17% of those of 2010 by 2015. Deploying CO_2 emission reduction technology in Shaanxi is therefore essential. As an important CO_2 reduction emission technology, early CCUS demonstration will be an important development in Shaanxi, which would enhance the province's national and international reputation. The government is supportive of a CCUS demonstration project in Shaanxi province.

There have not yet been any fully linked CCUS demonstration projects in Shaanxi. However, the Yulin natural gas chemical company employed CO_2 capture equipment in their facilities from 2004-

2010. Research and Development on low carbon technology has been conducted in Shaanxi province since 2004 and the academic community and government agencies have held numerous seminars and published many papers and reports on the topic.

1.2 Objectives and approach

The major objective of this work is to promote early opportunities for CCUS using high purity non-power industrial sources of Shaanxi, which may act as a catalyst for the larger scale deployment of the technology. A number of actions have been taken in support of this. Firstly, a review of the technical, policy, legislative and economic gaps and barriers relating to CCUS implementation in Shaanxi was conducted and reported.

The identification of a suitable CCUS demonstration project in Shaanxi Province would help to promote the wider deployment of low carbon technologies. To do this, inventories of suitable high purity industrial CO_2 sources and CO_2 sink industries of EOR and ECBM have been compiled. The information has been gathered from a combination of industry surveys and publicly available information in academic papers, reports and on the Internet. Based on a set of selection criteria and points system a number of potential CO_2 source-sink matches for a CCUS demonstration project were then identified and ranked for preference. During the course of the project a number of workshops were organised with attendance of relevant stakeholders from CO_2 source and sink industries and local government. The workshops brought together the involved parties thus facilitating dialogue on promoting CCUS and were used to disseminate the project findings.

2. Policy and Regulation for CCUS

2.1 Implementing an emissions trading scheme

Although there may be economic benefits for investing in CCUS with the combination of EOR, such business models may only be applicable in combination with a low cost (high purity) source of CO_2, a minimum transport distances and the suitability of the oil field in question. Furthermore, merely applying CCUS to high purity sources of CO_2 will not have a sizeable impact on China’s CO_2 emissions. These primarily stem from power generation and industrial production, which generally have lower concentrations of CO_2 in their associated exhaust streams. Therefore, in order to sustainably encourage the deployment of CCUS to maximise the technology’s contribution to CO_2 abatement, policy mechanisms will be required. This section introduces a number of these potential policy mechanisms.

A CO_2 emissions trading scheme, or cap-and-trade scheme, places an emissions cap on a number of identified installations in a geographical area. Emissions allowances are provided to the installations owners prior to the start of the trading period, either based on their existing emissions, or the government may issue fewer allowances in order to reach an overall emissions target for the emitters in the scheme. At the end of a verification period, operators must submit one allowance for every ton of CO_2 (or other pollutant) emitted. However, by investing in abatement technologies the operator can retain a number of allowances that can be traded for financial reward on a market platform. The principle of a cap-and-trade system is that operators who are able to reduce their emissions at the lowest cost will do so, leading to the lowest cost to emissions reduction for society as a whole.

The State Council's Energy Saving and Emission Reduction Working Plan in Twelfth Five-Year Plan (September 2011) aims to build up carbon trading market by launching ETS pilots and voluntary reduction mechanism. The NRDC government has encouraged establishing pilot emissions trading schemes in the Cities of Chongqing, Beijing, Tianjin, Shanghai and Shenzhen, as well as the Provinces of Hubei and Guangdong. The pilot schemes, announced in November 2011, aim to undertake the tasks of:

- Calculating the emissions cap
- Designing allocation plan for emission allowances
- Setting up the monitoring and registry system
- Building up the trading platform

The timeline for implementation of these ETS pilots is not yet clear. Calculating the emissions cap is key to determining the success of an emissions trading scheme. It is unclear how the emission cap will be calculated, as China has no absolute emissions target, however the CO_2 reduction target is based on CO_2 per unit of GDP. In 2009, the Chinese government committed to cut its CO_2 emissions per unit of gross domestic product (GDP) by 40% to 45% of 2005 levels by 2020. Subsequently, in 2011 the Chinese government set the target of 17% reduction of CO2 emissions during the Twelfth Five-Year Plan. The selection for CO_2 reduction based on emissions intensity can allow industrial growth to continue how in a less emission intensive manner. However, this form of CO_2 reduction is distant to the approach used in the United Nations Framework Convention on Climate Change's Kyoto Protocol, which has fostered the agreement of absolute emissions targets for a number of developed countries.

It is also unclear how the CO_2 intensity target can be transposed into a cap-and-trade system, as with the intensity target there is no actual cap on emissions. For example, in the European Emission Trading Scheme the fungible trading permit is equal simply to one ton of CO_2, whereas a trading scheme based on emissions intensity would require the development of a new metric (for example provincial CO_2 emissions/provincial output), or to convert the CO_2 intensity target based on projected GDP to the estimated emissions reduction requirement. Another question is how the intensity targets may be allocated regionally to reach the national intensity target.

Once the scope of the emissions trading scheme has been established, the method in which the permits are allocated is key to influencing what the eventual price of tradable credits will be on the market platform. If too many allowances are allocated then the price per credit will be too long to spur investment in any abatement technologies, whereas if the allocation is too strict the credit price will be high and could impact on regional competitiveness in trade, increasing the price of goods and power. For example, the first round of the EU ETS between 2005-2007 adopted the 'grandfathering' approach for allocation, distributing allowances based on previous emissions of the emitters. In some cases this led to windfall profits for certain companies as they were able reduce emissions relatively cheaply and retain a large surplus of credits. The other option is to 'auction' a percentage of the allowances at a cost equal to or close to the desired carbon prices in order to reduce the amount of allowances in the scheme.

In order for any emissions trading system to work, the emissions of the operator will need to measured periodically in order to the be reported to the governing authority. The measurements will also need to be verified by a third-party. Even if the emissions trading schemes start in certain sectors in separate regions, China should strive to ensure that the monitoring and verification techniques are consistent throughout the country. This is important so that in some point in the future, emission credits could be traded nationally and internationally.

Given NDRC and State Council announcements on emission trading and the significant piloting effort under way in five cities and two provinces, it seems likely that some form of emissions trading will be introduced in China in the future, possibly during the Thirteenth Five-Year period. However, the implementation modalities of such an ETS would likely significantly differ from current ETS we know elsewhere in the world and it remains highly uncertain if such systems will result in a carbon price in China that is high and stable enough to improve the economics of CCUS.

2.2 Regulation of CO_2 transport and storage

In parallel to the development and commercialisation of CCUS technologies, a legislative or regulatory framework is a key enabling factor for the deployment of CCUS in any country. However, akin to the majority of countries across the globe, no legal framework exists in China that can regulate this multifaceted and innovative abatement technology. Basically, effective regulation is essential to ensure that CCS operations are conducted in a manner that causes no harm to people and the environment. Furthermore, the development of a comprehensive regulatory framework is a fundamental step to ensure community and industry confidence regarding the capture, transport and storage of CO_2.

2.2.1 CO_2 transport and associated infrastructure

The regulation concerned with transporting CO_2 can be divided in two categories; i) regulation of the captured CO_2 itself; and ii) regulation concerning the development of CO_2 transportation infrastructure. The large-scale transportation of CO_2 is not a common activity in many countries. In China, the captured CO_2 may be classified as a waste product, and thereby the capture CO_2 could be exposed to existing legislation, which prohibits geological storage. In the EU Directive on the geological storage of CO_2[1], Article 35 amends Article 2(1)(a) of the Waste Framework Directive, categorically removing from the definition of 'waste', carbon dioxide captured and transported for the purposes of geological storage, provided it is geologically stored in accordance with the CCS Directive. Although having CO_2 classified as a waste does not prevent the movement of the substance, the movement and disposal of waste often has additional administrative and permitting requirements.

Another area of regulation that may be required concerns the purity of the CO_2 stream to be transported. Impurities in CO_2 streams can include nitrogen (N_2), oxygen (O_2) and water (H_2O), but also air pollutants such as sulphur and nitrogen oxides (SO_x and NO_x), particulates, hydrochloric acid (HCl), hydrogen fluoride (HF), mercury, other metals and trace organic and inorganic contaminants. The removal of certain contaminants may be required for health, safety and environmental protection reasons, but also to ensure the effective transport and storage of the CO_2 stream. The EU Directive of the geological storage of CO_2 does not place quantitative limits on the composition of the captured CO_2 stream, however it states that the stream should consist overwhelmingly of CO_2. This qualitative approach has been both praised, for providing flexibility in

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[1] Directive 2009/31/EC

the early stages of the development of capture systems, and criticised for creating uncertainty in the required stream specifications.

In terms of the regulation of CO_2 transport infrastructure, amendments may need to be made to existing Chinese regulations and potentially new legislation developed. As mentioned previously, in the EU Directive the requirements of EIA were extended to CO_2 pipeline developments. The Directive stipulates that pipelines with a diameter greater than 800mm and over 40km in length for the transport of CO_2, will be subject to a mandatory EIA. In China the State Environmental Protection Administration (SEPA) is responsible for overlooking that EIA are completed on relevant developments.

2.2.2 Storage regulation

Regulation must be developed that ensures the safe and long-term storage of CO_2. The backbone of a regulatory framework for CO_2 storage in any country must cover the following three elements:

- Selection and characterisation of the geological storage site
- Risk and safety assessment
- Monitoring

First, the prospective storage site must be characterised to assess its suitability. This stage involves sub-surface data collection using well logging to gain an insight into the permeability and porosity of the facies and seismology to understand the characteristics and rock layers that make up the storage formation. Once sufficient data has been collected, a static geological model can be developed. In order to test the performance of storage formation given the introduction of supercritical CO_2, dynamic modeling must be conducted. Dynamic modeling should show how the site will react, and from which a risk and safety assessment can be developed. The competent authority must then use these assessments to assess whether a storage permit can be issued.

A robust site-specific monitoring plan must also be developed prior to injection. The principal goal of monitoring is to verify that the CO_2 in the storage system is behaving as has been predicted by the geological model. The success of all monitoring techniques depends greatly on creating a robust pre-injection baseline, measured over a substantial period of time, against which all future measurements can be compared afterwards. Creation of such a baseline should enable to interpret monitoring results in case of significant irregularities or migration of CO_2 out of the storage complex. A monitoring plan should include both subsurface techniques such as 2, 3 and 4D seismic, down hole temperature and pressure measurements and geophysical logging, as well as shallow-focused monitoring techniques such as soil gas/surface flux measurements, tiltmeters, microbiology testing and bubble chemistry and measurement techniques (the latter in the case of offshore storage).

3. Investment for CCUS infrastructure

Finance for large scale CCUS is currently not developed in China. If cost-effective full-chain CCUS projects can be identified, it is possible that investment from the corporate and financial sector can be attracted to finance (parts of) these projects. For example, in the case of EOR the oil company that uses the CO_2 would invest in the CO_2 infrastructure at its injection sites. Financing options for the capture installations at the source industries depend on the nature of the contract between the Utilisation and the Source parties. A strong long-term contract with strong counterparties may be able to allow external financing or financing off the balance sheet of the parties involved. However, at present business models and commercial arrangements for establishing a full-chain CCUS project are undefined and therefore any notion on the source of finance remains theoretical.

The government could be a key source of finance for CCUS projects, both directly and indirectly. The Ministry of Science and Technology (MOST) has supported a number of CCUS demonstration projects (see Table 3.1)

Table 3.1 Existing and planned CCUS infrastructures in China.

Project	**Capture Method**	**Storage/Usage**	**Scale**	**Current Situation**
Beijing Thermal Power Plant Capture Project, Huaneng Group	Post-combustion Capture	Food industry, industry	3,000 tons/year	Under operation
Shanghai Shidongkou Power Plant Capture Project, Huaneng Group	Post-combustion Capture	Food industry, industry	120,000 tons/year	Under operation
Chongqing Shuanghuai Power Plant Capture Demonstration, China Power Investment Corporation	Post-combustion Capture	N/A	10,000 tons/year	Under operation
Jilin Oil Field CO_2-EOR R&D project, China National Petroleum Corporation	Natural Gas CO_2 Separation	EOR	0.8-1 million tons/year	Phase I finished; Phase II ongoing
Biodegradable Plastic Production using CO_2, China National Offshore Oil Corporation	Natural Gas CO_2 Separation	Biodegradable Plastic Production	2,100 tons/year	Under operation
CO_2-ECBM Project, China CBM	Purchase	ECBM	40 tons/day	Suspended
New Chemical Material Production using CO_2, ZHONGKEJINLONG Chemical Co., Ltd	CO_2 Captured From Alcohol Plants	Chemical Material Production	8,000 tons/year	Under operation
GreenGen Tianjin IGCC Demonstration, Huaneng Group	Pre-combustion Capture	EOR		Phase I ongoing
Lianyungang Clean Energy Demonstration	Pre-combustion Capture	Saline Aquifer Sequestration	1 million tons/year	Preparatory
Hubei Yingcheng 35MWt Oxy-fuel Combustion Demonstration	Oxy-fuel	Salt Mine Sequestration	100,000 tons/year	Preparatory
CCUS Demonstration, China Guodian Corporation	Post-combustion Capture	Food industry	20,000 tons/year	Preparatory

Microalgae Carbon Sequestration Bio-energy Demonstration, ENN Group	CO_2 Captured from Coal Chemical Industries	Bio-sequestration	320,000 tons/year	Ongoing
CCS Project, Shenhua Group	CO_2 Captured from Coal Liquefaction Industries	Saline Aquifer Sequestration	100,000 tons/year	Under Operation
Shengli Oil Field CO_2-EOR Demonstration, Sinopec Group	Post-combustion Capture	EOR	30,000 tons/year	Under Operation
CCS-EOR Demonstration			1 million tons/year	Preparatory

However, government funding levels have been mostly research focused and have been deployed at relatively small scale. Indirectly, the government can encourage investment in CCUS projects by the State Owned Enterprises that dominate the power, oil and gas and chemical industry sectors. In fact, in the largest CCUS demonstration project in China, the Huaneng Tianjin IGCC polygeneration and CCUS demonstration project, MOST has contributed 50 mRMB from the 863 funds of the overall 1.5 blnRMB investment for this project. The remaining investment in this case comes from Huaneng, one of the five large state-owned power generating companies in China. While this seems like a large investment in CCUS, it should be noted that the main part of the investment goes to developing an advanced IGCC project and CCUS is only a small part of the overall project.

One of the main areas for government finance in establishing a full-chain CCUS demonstration could be the transportation network. While transportation costs do not have to be a bottleneck for developing CCUS projects from a mere cost perspective, government investment for basic infrastructure, to which sources and sinks can connect, can help to reduce the risk of investment in capture or storage infrastructure. A basic transportation backbone will ensure easier access to a wider set of sources and sinks, therefore providing better insurances that stable CO_2 supply and demand can be maintained cost-effectively throughout the life of the project. Furthermore, the government can finance infrastructure at more favourable conditions, thereby lowering the cost of transportation. With the resulting reduced market risk and lower transportation cost, the risk profile of a capture and/or utilisation investment significantly improves, thus enhancing the various financing options to both source and utilisation industries.

4. EOR storage and other utilisation options in Shaanxi Province

As is widely acknowledged that CO_2 can be utilised to enhance coal bed methane (ECBM), to enhance oil recovery (EOR) and to enhance gas recovery (EGR). Shaanxi Province is rich in coal and gas resources, and it has some large oil fields. Therefore, Shaanxi Province has great potential to store and utilise CO_2. Also, Shaanxi Province is the core of the Chinese coal chemical industry and the CO_2 can be utilised in chemical plants.

4.1 Assessment of EOR storage capacity

Sequestrating CO_2 in depleted oil and gas field allows for storage of CO_2 by the exploiting of oil and gas. Assuming that all the room that was filled by minable oil and gas underground can be replaced by CO_2, then the CO_2 capacity in oil or gas fields can be calculated by the following equation:

$$V_{CO_2} = (V_{oil(stp)} / 1000) \times B_0 \times \rho_{CO_2} \qquad \text{(Eq. 1)}$$

In the equation, VCO_2 is the CO_2 capacity Mt; Voil(stp) is the volume of minable oil in standard condition; Bo is the reservoir volume coefficient, non-dimensional; ρ CO_2 is the density of CO_2 in reservoir conditions.

Hendriks (2004) and Christensen (2003) estimate the potential CO_2 sequestration volume around the world – depleted oil and gas fields in China have a CO_2 capacity of 10 billion tons at most.

4.2 EOR potential

CO2-EOR is an important technology for CCUS – it can both reduce the emissions of greenhouse gases and promote the production of oil, and thus will make some benefits. According to the current geological investigations, the potential of CO2-EOR is about 1600urrent geologibarrels, which is about 15% of the EOR production in the world. Most of the CO2-EOR projects are in the USA.

In 2008, EOR production in the world was 186.1Id. Most of the ; CO2-EOR production was 27.25e world was 186.; that is 15.1% of the total EOR production. That is far less than steam-EOR production, which is widely used in oil fields. But with the development of CO2-EOR, it will replace steam-EOR gradually. For instance, the USA has realised the industrial application of CO2-EOR in 2008, 105 CO2-EOR projects were built with a production of 25-EOR, it will replace steam-EOR gradually. ermian basin. That is 38% of the total EOR production and 91% of the CO2-EOR production in the world. In addition, the number of CO2-EOR projects in the USA is 85% of the world.

China's national ministry of science and technology approved 'greenhouse gas-EOR resource utilisation and underground storage' supported by the 'National Key Basic Research Development Plan' in 2006. China National Petroleum Corporation (CNPC) settled a major science and technology project 'greenhouse gas CO_2 resource utilisation and underground storage' in 2007. CNPC also settled a major pilot test 'Jilin Oilfield CO2-EOR and CO_2 underground storage pilot test' in 2007. Thus, CO2-EOR and CO_2 underground storage research has come into a new stage.

In China, gas fields fit for CO_2 storage have reserves of 35×108 tons, increased recoverable reserves could reache 3.5×108 tons from about 11 fields that are fit for CO2 storage. There has also been research on deployment of CO2-EOR, cost-effective CO_2 capture, CO_2 transport, corrosion and scaling. Meanwhile, PetroChina carried out a CO2-EOR and storage pilot test. From these activities in CO2-EOR and storage, we can see the giant potential in CO2-EOR.

4.3 Changqing Oilfield Company

PetroChina Changqing Oilfield Company (PCOC) headquartered in Xi'an is a regional oilfield company subordinated to PetroChina. The primary business of Changqing Oilfield Company is the prospecting, exploration, development, transport and marketing of oil, natural gas and symbiosis, associated resources and non-oil and gas resources in Erdos and its peripheral basin.

The exploration area of Changqing Oilfield is mainly located in the Shaanxi-Gansu-Ningxia basin, an area of 370,000km^2. Oil and gas exploration began in 1970 – three gas fields and 19 oil fields were exploited and the total oil and gas reserves found to be about 541,888,000 tons (233.008 billion m^3 natural gas reserves included, calculated in equivalent amount of crude oil reserves).

Changqing Oilfield realised an increase in production from 10 million tons to 20 million tons in the four years from 2003 to December 2007, becoming the second largest oilfield in China following Daqing Oilfield. To the end of 2007, Changqing Oilfield has exploited 106 million tons of crude oil and 49.7 billion m^3 natural gas.

Mineral resources registered area of Changqing Oilfield is 257,800 km^2 across five provinces and seven basins (14% of the total registered area of PetroChina). Changqing Oilfield has become China's important energy base and main battlefield of oil and gas production. In 2009, Changqing Oilfield exploited 30 million tons oil and natural gas, which makes it the second largest oilfield in

China. In accordance with the planning objectives of PetroChina, Changqing Oilfield Company's goal in 2015 is to exploit 50 million tons of oil equivalent.

4.4 Shaanxi Yanchang Petroleum Group

Shaanxi Yanchang Petroleum (Group) Corp. Ltd. (abbreviated as Yanchang Petroleum Group), directly attached to Shaanxi People's Provincial Government, is one of the four qualified enterprises for oil and gas exploration in China. Yanchang Petroleum Factory was established in 1905; In 1907 it drilled the first oil well in mainland China; and in 1944, Mao Zedong wrote the inscription 'Immerge in hard work'. Since China adopted the 'Reform and Opening-up' policy, Yanchang Petroleum has adhered to 'Supporting the enterprise via oil, combining mining with refining, and rolling developing'. In 1998 and 2005, two great restructurings took place, resulting in the integration and reorganisation of Shaanxi Yanchang Petroleum (Group) Co. Ltd. In 2010,it ranked No.72 in the top 500 Chinese companies, No.69 among top 200 Chinese companies with best profit, and No.16 among top 200 Chinese corporate taxpayers.

Shaanxi Yanchang Petroleum (Group) Corp. Ltd. is a newly built petroleum and chemical enterprise according to the Act to Reshuffle Northern Shaanxi Petroleum Enterprises by the provincial CPC committee and government. It is one of the four enterprises in the country that are entitled to explore and mine petroleum and natural gas. Businesses include oil and gas exploration, engineering construction, technical research and development, equipment manufacturing, oil and gas development, petrochemical engineering, oil refining, comprehensive chemical engineering of oil, gas, coal, and salt, pipeline transport, etc. The company leaders attach great importance to energy conservation, and make the conservation targets and duties clear for all levels after signing the Eleventh Five-Year Plan energy conservation target and duty contract. To ensure that the target is met, the group gives great priority to the work of energy conservation. Through analyzing the present situation and applying new technologies, skills and facilities, the company achieved good results in its energy conservation work and met the requirements of the state and the provincial committee of development and reform.

4.5 Other utilisation options

CO2-ECBM：CO_2 underground storage is an effective measure to reduce CO_2 in the atmosphere and alleviate the greenhouse effect. CO2-ECBM can reduce CO_2 emission as well as promote coal bed methane (CBM) yield and decrease the cost of CO_2 underground storage. CO2-ECBM is a safe and reliable way to store CO_2 by adsorbing CO_2 in the coal matrix. China has abundant coal resources; coal seams are widespread all around China. Therefore, CO2-ECBM can be the preferred choice of CO_2 underground storage. According to coal and CBM exploration data in China, the reserves distribution of different coal, and the replacement ratio of CO_2 and CH4, we conducted a preliminary evaluation of CO_2 storage capacity in coal seams, which are about 300–5000 meters deep and rich of CBM. The result indicated that minable CBM in China can reach 1.632×1012m^3, meanwhile that would be able to store 120.78×108 tons CO_2 which is about 3.6 times of China's CO_2 emission in 2002.

Food industry：In the food industry, CO_2 is used for food refrigeration, sterilisation, mildew proof and retain freshness, etc. In order to adjust the competition in international food markets and meet domestic high-end food preservation needs, this will be a potential market of liquid and solid CO_2.

Also, CO_2 can be used as additive of soda drink, beer, cola and carbonated beverage. CO_2 consumption in west Europe is 1.6 million tons/year, 80% of this is liquid CO_2, mainly used for carbonated beverage and food, then for weld and refrigerated transport. Germany produces the most CO_2 by separating it from natural gas – more than 30 liquid CO_2 factories are located in Germany. It is forecast that CO_2 consumption, which consists of 80% liquid CO_2 and 20% solid $CO_{2,}$ will increase by 3–4% in the next few years in western Europe. In China, the beverage industry is the largest CO_2 consumer, taking about 30%. However, drink consumption per person is less than five kilos/year; while in the USA it is 150 kilos/year and in western Europe it is 110 kilos/year. As the improvement of people's living standards in China, CO_2 consumption in the beverage industry will significantly increase.

Plastic material: Using CO_2 as chemical feedstock to produce plastic has taken shape globally. In recent years 110 million tons of CO_2 has been sequestrated through this chemical method every year. Urea is the largest product sequestrating CO_2, consuming more than 70 million tons every year. Inorganic carbonate is the second largest, consuming 30 million tons per year. Hydrogenation of CO_2 to synthesize CO also consumes six million tons CO_2. Twenty thousand tons of CO_2 is used for synthesize salicylic acid and propylene carbonate, which is used for drug manufacturing.

Synthesized urea with CO_2 and ammonia is the most successful example of sequestrating and using CO_2. Based on urea, we still can produce dimethyl carbonate with $CO_{2,}$ making urea an effective carrier of CO_2. Replacing phosgene by CO_2 to synthesize high value-added chemical feedstock (dimethyl carbonate, isocyanate, methyl methacrylate, etc.) can realise cleaner production; while at the same time reacting at mild conditions so as to improve the economy and security of the process.

At present, CO_2-based plastic represented by CO_2 and epoxide copolymers is also a hot issue. This kind of plastic is biodegradable which makes it helpful to resolve the 'white pollution' problem. China National Offshore Oil Corporation (CNOOC) and Inner Mongolia Melic Sea High-Tech Group Company, representing the most advanced CO_2-based plastic industrial technology in the world, have built two production lines of thousand-tons-level. Henan Tianguan Group has also built a CO_2 copolymer pilot plant with its self-initiated catalysis system. Low molecular weight of CO_2 copolymer technology, researched by Guangzhou Institute of Chemistry, Chinese Academy of Sciences, has been used in Taixing, Jiangsu – this technology uses a low molecular weight of CO_2 and epoxide copolymer as feedstock of polyurethane foam materials.

5. Analysis of logistical challenges to CCUS

To some extent, developing CCUS in China faces a more complicated situation than other countries. For instance, there are challenges, such as potential safety hazards, high energy penalties, match of CO_2 sources and sinks, evaluation of storage potential, cross-industry cooperation, financial facilities and public awareness. Many of these challenges are derived from the uncertainty of technology; so technological breakthrough is the key to implementing CCUS in China. Besides, a well developed methodology, standards and regulations system can help to solve these problems; and obviously that demands the government's guidance and support, and the participation of enterprises, academia, NGOs and the public.

5.1. Location of EOR sites in comparison to high purity CO_2 sources

China's distribution of CO_2 potential storage site and energy consumption center brings a big challenge in terms of matching CO_2 sources and sinks, transport path plans and means of transport. China's energy consumption center is in the east, while the potential storage site is in the west. Transporting the CO_2 captured in the east to the storage site in the west could have high associated costs bring safety risks to the environment and the public.

EOR sites in Shaanxi Province are mainly the Yanchang Oilfield and Changqing Oilfield. Yanchang Oilfield is located at Yan'an (Yan'an, Yulin, Inner Mongolia included), Shaanxi Province. It started to produce oil with indigenous method in 1905 (the first onshore oil well in China-Yan No.1 Well, 80 meters deep, produce 1–1.5 tons oil per day). To 1948, Yanchang Oilfield produced 6,115 tons raw oil. In 1949 it produced 802 tons raw oil and 176 tons gasoline, which supported the People's Liberation Army marching into the Northwest. Yanchang Oilfield deployed more exploration and construction project after liberation. Its raw oil production reached 150 thousand tons in 1985. Till 1998 it already had 10 well-drilling companies, producing 1.7522 million tons raw oil per year. After reshuffle in 2005, its raw oil production grew even more rapidly. In 2007 its production exceeded 10 million tons and in 2009 its production reached 11.2 million tons.

Changqing Oilfield has proven geological oil reserves of about 335.79 million tons, controlled reserves of about 394.04 million tons and prognostic reserves of about 532.75 million tons since 1999. Four mainly oil fields of Changqing are Shanbei Ansai, Jing'an, Suijing and Wuqi.

There are many CO_2 sources suitable for CCS demonstrations in Shaanxi Province. These sources are mainly methanol, dimethyl ether and synthesis ammonia plants, which have high-concentration CO_2 emissions. As these CO_2 emissions cost relatively less to capture and they don't need too much pre-treatment before transport, it's an ideal choice to deploy early CCS demos in these industries. CO_2 sources are mainly located at heavy chemical industry bases in Yulin, north Shaanxi and Weinan, south Shaanxi. Yulin District has abundant coal and natural gas resources; it's an ideal site for CO_2 geological storage where CO2-ECBM can be deployed. Yan'an District also has many high-concentrated CO_2 sources. Some of these sources are owned by Yanchang and/or Changqing Oilfield and can be used for CO2-EOR.

In conclusion, as China's heavy chemical industry base, Shaanxi Province has abundant CO_2 sources, as well as huge CO_2 storage potential. All these factors make it convenient for early CCS demonstrations.

5.2. Current CO_2 emission levels and potential EOR usage rates

The evaluation of the CO2-EOR potential is also a challenge of implementing CCUS in China. In order to know the CO2-EOR potential we must first understand the basic information of the oil/gas fields. For those oil/gas fields that have been mined, we can use the stimulated reservoir information as a reference – whether the chosen oil/gas field is suitable for long period CO2-EOR and how much CO_2 it can store needs further research. For a long time, the oil field reservoir information was in the hands of a few oil giants and not available to the public. In order to acquire this information we must promote multi-cooperation and even attract the government to take part. An initial evaluation shows that the total CO_2 storage potential in China is 3,088 Gt, of which the saline aquifer storage potential is 3,066 Gt and the oil field storage potential is 4.8 Gt.

The CO_2 emission levels are different according to different plant types and scales. Table 5.1 lists the CO_2 emission scale of different CO_2 sources.

Table 5.1: Current CO_{2f} emission levels

Type	CO_2 source	Emission scale
Power Plant	Fuel-Coal	7.5–60 million tons/year
	Fuel-Oil	3.75–30 million tons/year
	Fuel-Gas	3–24 million tons/year
Alcohol/Methanol/Dimethyl Ether Plant	Alcohol/Methanol/Dimethyl Ether Plant	0.25–2.5 million tons/year
Steel Plant	Steel Plant	2–10 million tons/year
Cement/Building Materials Factory	Cement Plant	0.1–2 million tons/year
Oil refining/Chemical Plant	Refinery	0.1–0.6 million tons/year
	Ethylene Plant	0.25–2.5 million tons/year
	Ethylene Oxide Plant	0.2–1 million tons/year
	Hydrogen Plant	0.2–0.6 million tons/year
Fertiliser Plant	Synthesis Ammonia Plant	0.38–3.8 million tons/year

Currently, there are already some commercial CO2–EOR projects: Canyon Reef, Bravo Dome, Cortez, Weyburn and Sheep Mountain. One of these, Weyburn Oilfield in Canada, has a CO_2 transport capacity of five million tons/year, the typical composition of the material flow was: CO_2 96%, H2S 0.9%, CH4 0.7%, C2 + 2.3%, CO 0.1%, N2 <300ppm, O2 <50ppm, H2O <20ppm (UK Department of Trade and Industry, 2002).

At present, 11% of the USA's CO_2 consumption is used for CO2-EOR weighing 530,000–550,000 tons/year. China has launched several CO2-EOR research projects in the Xinjiang, Daqing and Shengli Oilfields, accumulating some data and practical experiences.

6. Technical Opportunities and Challenges

CCUS, which includes the capture, transportation and potential underground storage of CO_2, has some serious issues due to the complex nature of the transported material. Small fluctuations in temperature and pressure can lead to sudden and drastic changes of the CO_2 physical properties, that is, phase and density. Multiphase flow within CCUS systems is undesirable because it leads to inefficiency; this must be carefully controlled and presents technical challenges.

The following sections analyse the technical challenges and opportunities relating to a CCUS demonstration and wider deployment of CCUS infrastructure in Shaanxi. The aim of the analysis is to identify specific areas of the concept, which may require further assessment in later phases of development. The potential to share CCUS infrastructure such as pipelines will be heavily dependent of location and route considerations; this is discussed in the next section.

6.1. CCUS infrastructure sharing

After a successful demonstration project, CCUS can be introduced on a larger scale. Clusters of projects may emerge, incorporating multiple emitters and sink industries that could work collaboratively to share capture and transport infrastructure. The development of CCUS clusters has a great potential for providing access for additional industrial stakeholders to CO_2 and of sharing costs so that they are considerably below that of developing each project on an individual basis [1].

As early opportunity CCUS applications propose to use already available high purity industrial CO_2 sources, only a relatively small amount of extra process equipment will be needed for the capture section of the CCUS chain. The main requirement would be to compress the CO_2 to high pressure, usually >100 bar. It may also be necessary to dehydrate the CO_2 stream prior to transport. The potential to share facilities for CO_2 compression, dehydration and liquefaction could be explored for CCUS clusters because this may be more economic in terms of both capital investment required and operational costs compared to standalone projects.

The presence of free water in the CO_2 stream is a serious corrosion risk to the carbon steel of the internal pipeline system due to the formation of carbonic acid. The use of corrosion resistant materials may be considered but is unlikely to be economically feasible for long pipeline systems. Therefore, the CO_2 stream must undergo a dehydration process to remove virtually all of the water being transported any substantial distance by pipeline. For this reason, it is unlikely that the sharing of dehydration equipment will be feasible.

CO_2 compression is required prior to its transport via pipeline and for most of its applications and uses. Compressors usually change the phase of CO_2 from gas to either liquid or the supercritical phase – this is done to increase the density and therefore reduce the volume of the fluid, allowing a reduction in the size of the pipeline diameter. Significant operational costs can be incurred at the compression stage so the use of compressors should be minimised where possible, although there will be an economic trade-off between pipeline diameter. Design and operation of the compression infrastructure and a pipeline network must consider the possibility of phase change as the pipeline moves into different local environments. Pressure drop along the transportation pipeline must be taken into account so that CO_2 is delivered to its application at the intended pressure and phase. Shared compressor systems might be located near groups of industrial CO_2 emission sources or at other locations across a CO_2 pipeline network; the locations should be based on techno-economic assessments in order to optimise the energy requirements and use of steel materials.

For small emitters of CO_2, or for when smaller amounts of CO_2 are required for small-scale demonstration, it may be possible to use road tankers for short distance transportation. Road tankers have been used to transport CO_2 for over 40 years – each tanker can hold up to 20 tons of CO_2 [2] and it is generally considered to be a safe method of transporting CO_2. Where road tankers are used, CO_2 must be compressed onsite before using the road network. In addition, the CO_2 sink industry may require CO_2 storage tanks and additional transfer facilities. A drawback of this approach is the large cost, the environmental impact of fuel usage and the scale limitation.

When considering the engineering opportunities and challenges for CO_2 handling and transport, it is important to discuss the health and safety issues. Although CO_2 is benign at the kinds of concentrations usually encountered in the natural environment, it is an asphyxiant gas at the high concentrations of those of CCS applications and can be considered as a hazardous substance. A major release of CO_2 from a CCS system, would pose a significant risk to any nearby populated areas because CO_2 is denser than air and therefore has the potential to accumulate in low-lying areas under the right conditions. The consideration of odorants may be worthwhile in high consequence areas [3].

In the event of pipeline depressurisation or loss of containment, the escaping CO_2 will experience a sudden change in phase as the CO_2 rapidly expands and a proportion vaporises. In addition, dry ice projectiles being expelled at very high velocities may result. Other hazards include cryogenic burns to the skin and catastrophic failure of carbon steel equipment due to low temperature metal embitterment [4]. The pipeline must be designed to mitigate the health and safety risks by consideration of the route, buried depth, pipeline thickness and others. In possibility of CO_2 pipeline rupture must be considered; risk assessments must consider pipeline block-valve spacing philosophy however including too many valves from the compressor to the injection or storage point can also be a problem due to the creation of extra potential leakage paths. All pipelines should have both operating and emergency pressure-relief systems. Designers must ensure that adequate procedures are in place to handle leaks and that there is a risk review process, which includes an emergency-response team [5]. Stakeholders should build a shared understanding of the risks associated with CCUS and develop mitigation strategies.

Pipeline sharing for the wider scale deployment of CCUS represents the most cost effective and technically viable option for transportation of CO_2. The economic benefits mainly arise from the economy of scale, increased reliability, lower barriers to entry and consolidation of planning issues. A larger trunk pipeline with multiple CO_2 sources would be better able to cope with fluctuations in delivery. A networked approach would also reduce environmental damage and public inconvenience by avoiding the construction of multiple pipelines along similar routes within a relatively short timeframe. However, in order to establish a networked approach it may be necessary to initially oversize the pipeline infrastructure and this brings financing issues which maybe too risky for individual organisations; therefore government co-funding is likely to be necessary. The co-ordination of operations between multiple sites for CO_2 transportation networks is another technical difficulty.

Four potential point-to-point CCUS demonstration projects for CO_2-EOR have been identified during the course of this project. For three of these, pipeline has been identified as the most economical method for CO_2 transportation and road tanker transport for the remaining one. The estimated CO_2 pipeline lengths required for the demonstration range from 40–170 km whereas the transportation distance for road tanker is 40 km. The terrain is largely fit for laying pipeline in Shaanxi Province and there are many existing pipelines.

Pipeline and compression infrastructure must be designed so that the arrival pressure is correct for the intended application. Pipeline design must also consider that reservoir conditions will change over the course of EOR operation and pressure will increase in response to CO_2 injection. Reservoir modelling must be performed to understand and predict the pressure changes during the CO_2 injection phase.

Operating regimes of CO_2 source industries will have an impact on CO_2 EOR operations due to fluctuating CO_2 flow rates. During short periods of increased volumetric flows, CO_2 can be temporarily stored in the pipeline itself, through a process called line packing. During periods of high demand, increased quantities of CO_2 can be withdrawn from the pipeline at the application area, than is injected at the production area. Longer term stoppages from CO_2 source operations, e.g., major and minor outages at chemical production plants, will require careful consideration which is likely to see the reservoir held at an equilibrium pressure for no flow periods.

The oilfield operators may also require stoppages. Where these are planned it would be sensible to coordinate these with scheduled emitter outages.

If there are significant future opportunities for additional CO_2 source industries to join a shared pipeline, it may be worth considering the sizing of the pipeline to accommodate these and installing tee joints during the pipeline commissioning phase. The tee joints would be placed at anticipated locations where future CO_2 source industries would join the major pipeline. Similarly, tee joints could be installed closer to multiple CO_2 sink industries where the pipeline may diverge in future. The tee joints would allow a much more economical connection in future and diminish the potential for interruption to the existing CO_2 pipeline. Where many tee joints would join a major CO_2 pipeline (e.g. a potential Yulin cluster), input pressures would need to be controlled at the junction points so that they match as much as possible to the pressure of the major CO_2 pipeline. A control system would be required to relay information to the compressor station of the CO_2 source industry.

To reduce the costs of implementing CCUS in Shaanxi, the reuse of existing oil and gas pipelines should be considered, such that these might be reverse engineered to take CO_2 to the oilfields from which the pipelines previously transported hydrocarbons away from them.

6.2. CO_2 impurity impacts

CO_2 quality levels are an important technical consideration for CCUS. Inadequate quality levels can negatively affect operations, maintenance and most importantly the safety of the CCUS system and the public. The effects and cross effects of impurities require a better understanding during dense phase CO_2 transport. Quality requirements that are too strict may result in a significant economic burden, due to the investment in gas cleaning facilities, operational costs and increased downtime.

The DYNAMIS European project [6] made recommendations on allowable impurity levels for transport via pipelines for pre-combustion and post-combustion processes. The impacts of the impurities on application of the CO_2 for EOR were also discussed. There are parallels that can be drawn from CO_2 sources derived from pre-combustion carbon capture power generation and high purity industrial sources of CO_2 derived from gasification, such as, coal-to-liquids (Fischer-Tropcsh) or ammonia/fertiliser plants. The concentration limits and an explanation of the technical or safety limitations are given in Table 6.1.

Table 6.1. DYNAMIS recommendations for CO_2 quality [6,7]

Component	**Concentration**	**Limitation**
H_2O	500 ppm	Technical: below solubility limit of H_2O in CO_2. No significant cross effect of H_2O and H_2S. Cross effect of H_2O and CH_4 is significant but within limits for water solubility.
H_2S	200 ppm	Health and safety considerations
CO	2000 ppm	Health and safety considerations
O_2	Aquifer < 4 vol%, EOR < 100 – 1000 ppm	Technical: range for EOR because of lack of practical experiments on effects of O_2 underground.
CH_4	Aquifer < 4 vol%, EOR < 2 vol%	Energy consumption for compression and miscibility pressure for EOR
N_2	< 4 vol % (all non-condensable gases)	Energy consumption for compression
Ar	< 4 vol % (all non-condensable gases)	Energy consumption for compression
H_2	< 4 vol % (all non- condensable gases)	Further reduction of H_2 is recommended because of its energy content
SO_X	100 ppm	Health and safety considerations
NO_X	100 ppm	Health and safety considerations
CO_2	>95.5%	Balanced with other compounds in CO_2

For the purpose of CO_2-EOR, CO_2 purity should be more than 94-95 vol.% in order to achieve miscible conditions in the oil reservoir. The Minimum Miscibility pressure (MMP), reservoir depth and the API gravity of the oil determine if the reservoir is suitable for CO_2-EOR. SO_2, H_2S and C_3+ species impurities in the CO_2 will decrease the MMP whereas O_2, N_2, Ar and NO impurities will increase the MMP. For CO_2 transport via pipeline to an EOR site, consideration must be given to impact the impurities could have on pipeline corrosion or phase change of the transported fluid [8]. The presence of SO_2 as an impurity could accelerate pipeline corrosion since this gas forms an acid when dissolved in water. Water levels should therefore be reduced to a certain level but to exactly what extent is controversial. Visser et al. recommends an upper limit of 500 ppm of H_2O in the CO_2 stream [6]. The presence of O_2 with H_2O can accelerate cathodic reaction leading to internal pipeline corrosion. The presence of impurities could result in the formation of a second liquid phase during the transport of supercritical CO_2, which could have consequences of flow instability and cavitation in the pipe. It would also lead to undesirable high and low pressure peaks that oscillate within the pipeline [9]. Most EOR operators recommend levels of oxygen to be below 10 ppm for reservoir safety reasons. In addition, impurities in the CO_2 stream may have an impact on sequestration. The CO_2 impurities can have the same corrosion impacts on well injection equipment as they do on pipeline equipment, which could affect injection well integrity.

6.3. EOR CO_2 injection

There are two main types of CO_2-EOR, namely; miscible flooding and immiscible flooding. Miscible CO_2 flooding is the most common form of CO_2-EOR and refers to when the injected CO_2 and oil mix to form a miscible fluid so that the interfacial tension between the two initial phases effectively disappears, enabling the CO_2 to displace the oil from the rock pores and push it towards the production wells. Immiscible flooding refers to when CO_2 and oil do not fully form a miscible mixture such with low-pressure reservoirs or for heavy crude oil where the mechanism for oil recovery is usually associated with gravity displacement.

It is anticipated that many of the existing oil production plants associated with the oil and gas fields in Shaanxi can be used to accommodated CO_2 pipeline and CO_2-EOR projects.

Chanqing oilfields

Most oil reservoirs in the Changqing Oilfield area are of low permeability and have entered middle development stages after several decades of production. They are therefore suitable for applying CO_2-EOR and CO_2 sequestration techniques. A recent study by Liao et al [10], assessed the potential of CO_2-EOR and storage in the Changqing Oilfields based on the data of 261 mature oil reservoirs. The assessments included regional geology assessments, storage site screening and reservoir screening for CO_2-EOR, EOR potential and storage capacity calculations. Of the 261 reservoirs, 113 were found to be suitable for miscible or near miscible flooding CO_2-EOR and storage. The total EOR potential is estimated to be 98 million tons and the CO_2 storage potential could reach 239 million tons. The average incremental oil recovery rate in reservoirs suitable for miscible or near miscible flooding conditions was around 12% whereas that immiscible flooding is thought to be around 7%. Greater potential for CO_2-EOR and storage is found in reservoirs with the greatest Original Oil In Place (OOIP) and hence these will be the preferred sites for CO_2 storage.

6.4. Flow rate measurement

Accurate measurement of the inventories of CO_2 throughout the CCUS process is an important part of the CCUS infrastructure and will be essential for the operation of these systems. This is required to identify if there are any potential leakages in the system, for aiding payments across different entities of the operating CCUS chain and to account for carbon under any future potential Emission Trading Schemes. The detection of any leakages will be important to CCUS regulatory bodies.

There are significant challenges with measuring the quantities of CO_2 captured, transported and stored which relate to the physical properties of CO_2 and the CCUS operating conditions. These have been reviewed by TUV NEL [11] and are as follows:

- To keep CO_2 in the desired phase, CCUS systems are likely to span a relatively narrow range of temperature and pressure. However, at these conditions, phase variability between gaseous and liquid flow is still a possibility, creating a significant challenge to accurate measurement since flow meters are generally designed for one specific phase. Therefore, phase boundaries for CO_2 and CO_2 mixtures need to be established along with an accurate model for density within the gas, liquid and supercritical phases.

- The presence of impurities adds another layer of complexity, which will be especially apparent when multiple CO_2 source industries join a shared pipeline. This can be alleviated by using accurate sampling techniques need to be developed to determine the CO_2 content in the captured gas and to determine the purity of CO_2 transported into the CCS pipeline infrastructure, by using a Continuous Emissions Measurement System (CEM) for example. However, for CEMs to work accurate physical property models at the temperatures and pressures that prevail in CCUS applications are needed.
- There are considerable gaps in knowledge on CO_2 flow metering. Although CO_2 flow measurement has been done in the US for some time, there has been no appraisal of their performance. The reliability of flow metering technologies and associated instrumentation should be assessed for CO_2 and CO_2 mixtures over a range of test conditions.
- The relevant industries involved in CCUS require guidance on monitoring and reporting CO_2 flows.

The first flow metering location should be post capture and prior to entry to the CO_2 pipeline. The main types of flow meters that have been previously used in EOR applications are Orifice Plate Meters, Turbine Meters, Ultrasonic and Coriolis meters. Amongst these, Ultrasonic and Coriolis meters have undergone recent developments, which may make them suitable for CCUS applications. Venturi and V-cone meters have no known experience in CO_2 applications; however the latter have been used for multiphase flow. Research into improving CO_2 flow metering is ongoing [11].

6.5. Monitoring CO_2 storage sites

The safe geological storage of CO_2 will depend upon the use of appropriate operational practices, regulations, monitoring and materials [12]. Detailed plans for CO_2 monitoring at storage sites are likely to be needed in order for a licence for EOR to be issued. Rigorous monitoring of CO_2 storage sites is done for a number of reasons; including:

- To detect any leakage of CO_2
- To provide confidence of long-term storage integrity
- To provide early warning of significant irregularities
- To test and compare conventional modelling predictions with actual CO_2 flood movements in the storage site
- To observe any migration of CO_2 in the reservoir.

The monitoring of CO_2 storage sites represents a considerable long-term commitment for storage site operators and present a range of technical challenges. There are a number of approaches to CO_2 storage site monitoring, such as:

- Acquiring baseline measurements against which subsequent monitoring is compared
- Production data sampling of well pressures and volumes of injected and produced fluids

- Measurement of changes in reservoir fluid chemistry
- Seismic imaging of reservoir properties
- Recording of microseismic activity in the reservoir
- Sampling of surface soil gas for detecting traces of leaking CO_2.

7 Options for an EOR demonstration project integrated with an industrial high purity CO_2 source

This project has identified four CO_2 source-sink matches for a potential CO_2-EOR demonstration project. These are:

1. EOR at Jingbian oil exploitation plant in Jingbian County, using CO_2 captured from Yanchang Oilfield methanol plant
2. EOR at Yanchang Petroleum Zhiluo oil exploitation plant in Fu County using CO_2 captured from Yanan Fuxian methanol plant
3. EOR at Changqing Petroleum 4th oil exploitation plant in Yulin Changqing industry base, using CO_2 captured from Changqing Oilfield methanol plant
4. EOR at Changqing Petroleum 4th oil exploitation plant in Yulin Changqing industry base, using CO_2 captured from Jingbian methanol plant

The locations of these facilities in Shaanxi Province are shown in Figure 1.

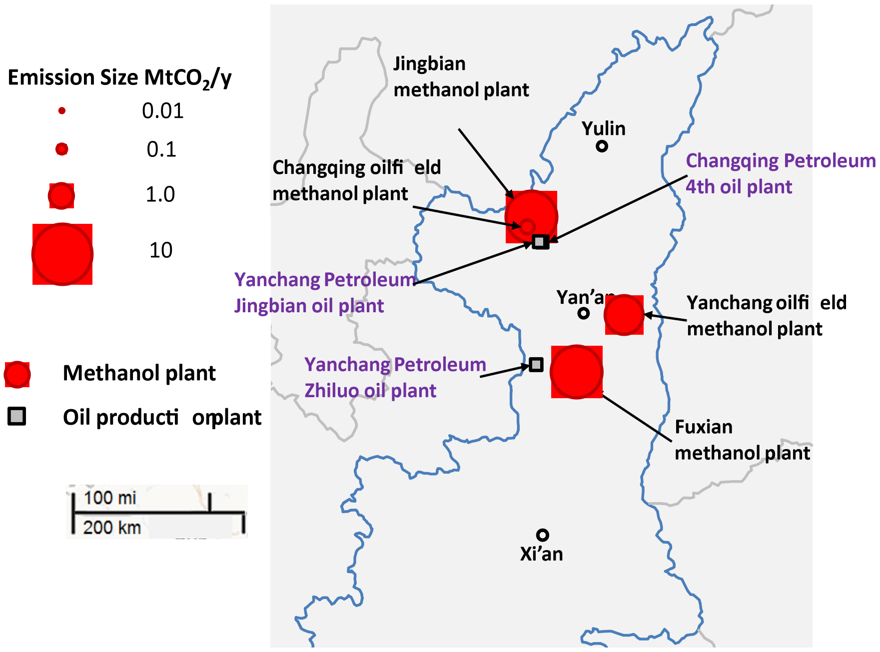

Figure 1. CO_2 sources and EOR sites for suggested demonstration projects in Shaanxi Province.

These options have similar estimated costs for capture and EOR injection costs (per ton of CO_2 handled) but transport costs differ. These options are not necessarily mutually exclusive but could complement each other, for example in a mini-cluster based approach. They would all use CO_2 captured from methanol plants where steam reforming of coal or methane is performed to produce a feed gas and also generates an exhaust gas rich in CO_2.

7.1 EOR in Yanchang Oilfield, Yanan, using CO_2 captured from Yanchang Oilfield methanol plant

The Yanchang Oilfield methanol plant produces 99% purity CO_2 at a rate of 3.25 million tons/year. The entire amount of CO_2 could be utilised for EOR in oilfields located. The total CCUS cost after consideration of the benefits to the oil industry has been estimated to be between -50.4 and 5.6 $/t$CO_2$. This option has a pipeline transportation distance at 160 km giving it a transportation cost at 1.6 $/t. This project is believed to bring the most economic benefit out of the four demonstration projects.

7.2 EOR in Yanchang Oilfield, Yanan, using CO_2 captured from Yanan Fuxian methanol

The Yanan Fuxian methanol plant produces 6.8 million tons/year of 99% purity CO_2, which could all be potentially be utilised in the Yanchang Oilfield near Yanan for EOR. The source to sink CO_2 pipeline distance has been estimated to be 170 km, giving this a slightly higher transportation cost of 1.7 $/t. The total CCUS cost after considering the benefit to the oil industry is estimated to be between -47.3 and 5.7 $/t.

7.3 EOR in Chanqing Oilfield, Yulin, using CO_2 captured from Changqing Oilfield methanol plant

Utilising the 250,000 t/y of high purity CO_2 produced by the Changqing Oilfield methanol plant in EOR at Chanqing Oilfield, Yulin, has been identified as another potential CCUS demonstration project. This would be a smaller operation due to the smaller volume of CO_2 being utilsed. As a result, road tanker transportation has been deemed to be the most effective method of CO_2 transportation over 40 km, albeit at a higher cost of 3.2 $/t$CO_2$ transported. The total CCS cost when considering the benefit brought by enhanced oil recovery has been estimated to be between -45.8 and 7.2 $/t CO_2.

7.4 EOR in Changqing Oilfield, Yulin, using CO_2 captured from Jingbian methanol plant

The source-sink matching procedure identified one additional option for an EOR demonstration, which was to apply it to Changqing Oilfield using 6.8 million t/y of high purity CO_2 captured from Jingbian methanol plant in the northwest of Shaanxi. Pipeline transport would be used for this option over a relatively short distance of 40 km and the total cost after taking into account the benefit brought by EOR was estimated to be between -48.6 and 4.4 $/t making this option economically attractive.

8. Commercial Arrangements

8.1. Drivers for CCUS

It is helpful to set out the following discussion on commercial arrangements with a summary of the main drivers for high purity CO_2 source industries and oil field operators in Shaanxi to invest in CCUS infrastructure, as follows:

- CCUS gives emitters of high purity source industries the opportunity to sell their CO_2 rather than venting to atmosphere.
- Potential future regulation for chemical process industry on reducing CO_2 emissions
- Injecting CO_2 into an oil reservoir can increase the recovery rate therefore increasing the profitability of the petroleum activity.
- Shortages of large volumes of water that are needed for efficient secondary recovery.
- Preserves natural gas reserves, which may otherwise have been used for gas injection.
- Funding from the Ministry of Science and Technology.

Sections 8.2 and 8.6 provide details of the important issues surrounding emerging commercial arrangements, which will be required to develop CCUS projects and possible future clusters.

8.2. Roles of CO_2 sources and sinks

Demand for CCUS infrastructure will be driven by both industrial sources of CO_2 and EOR operators because both industries stand to profit from the activity and can both generate revenues from these (via CO_2 sale for source industries and increased oil sales for sink industries). As a result, CO_2 source and sink industries could be expected to form partnership proposals that lead consortia of organisations bidding for funding from the MOST. It is likely that contracts would be agreed upon, whereby revenue generated by the activity from source and sink industry would be passed to transport and other storage elements (e.g. storage monitoring), whether these are owned by the source or sink industries or are outsourced to external companies.

The policy and regulation of CCUS outlined in Section 2 is likely to cause additional CO_2 source industries to seek further development or access to CCUS, leading to the extension of the duration of operation of CCUS and future expansion of the infrastructure. However, the high capital investment costs means that CCUS will not be economically viable without public funding for some years. A successful demonstration in Shaanxi should alleviate some of the financial risk and bring down some of the costs such that a range of CO_2 source and sink industries could join CCUS in a cluster based approach.

8.3. EOR, Licensing, Business models and risk transfer

Significant business risks associated with the integration of CCUS technologies exist and would be carried by developers of the required infrastructure. Worst-case scenarios could lead to significant stranded assets.

Some issues await the assessment and granting of licences for CO_2-EOR and how to tax the production of additional oil reliably and securely. However, one advantage that CO_2-EOR has over other storage options is that it is usually permissible within existing petroleum licensing agreements [13]. Nevertheless, there may be some requirements to modify laws so that EOR operations can be converted to dedicated storage sites for climate measures. The business principle of this is based on the avoidance of purchasing carbon credits. In China, licensing of CO_2-EOR is likely to be handled by the NDRC or state council.

A business idea related to CO_2-EOR is to sell CO_2 to the oil and gas producing licenses at regulated prices, whereby the pricing of CO_2 sales follows the oil price. The financial risk associated to investment in CCUS infrastructure would be too high for oil companies due to possible low profitability from low oil prices. The state usually has high revenues from production tax as well as equity in hydrocarbon resources, therefore CO_2-EOR will be profitable even at very low oil prices. The use of variable price fixing of CO_2 delivered to the fields based on the current oil and gas prices reduces the financial risk for production licenses since the price of CO_2 will be very low at low oil prices [14].

In addition, through the capture and storage of millions of tons of CO_2, China would potentially avoid the need to purchase carbon credits on the international market. This reduction in carbon credit costs derives directly from the establishment of CCUS and should therefore be part of the state's economic assessments of the investments and operating costs the CO_2 source and sink industries incur.

No financial security currently exists for CCUS. CO_2 source industries like methanol plants are dependent on a secure and continuous sale of CO_2 in order to defend significant investments in CO_2 capture and compression equipment. Oilfield operators, being the potential buyers, are dependent on significant volumes, probably larger that single sources in Shaanxi can supply. Oilfield operators also require flexibility in supply, which may incur intermediate CO_2 storage. Investment decisions are made in each license where owner shares are held by many companies. Greatest profitability can be achieved when the investment costs for CCUS are shared in several licenses. Investment decisions can be hindered when all of the investment for CCUS infrastructure falls on the first of licenses. CCUS infrastructure could be used by several licenses and has a longer lifetime than individual licenses; it would therefore be advisable to create financial instruments that make cost sharing between licenses over a longer time frame feasible.

Due to the large taxes on petroleum activities, large financial rewards from increased incremental oil recovery are gained by the State. The interests of the state and industries are not necessarily shared. The state that owns the oil reserves of Shaanxi seeks to extract as much oil from each field as possible and uses different measures to achieve this. Any remaining oil in the field after closure represents an economic loss to the state. For the oilfield operators, the main objective is to secure as a high a return on invested capital as possible. As the state stands to profit from CO_2-EOR it seems logical that it should carry some of the risk, which may be achieved through a modification of taxation system. For example, tax exemptions could be applied by government to secure the oilfield operators a defined regulated return on investment for CO_2-EOR projects. This should be defined through agreements between the government and the individual license. In this way, the state assumes some of the risk but also the financial reward [14].

Financial risks for CCUS would be expected to diminish in future due to the ability of industries to take advantage of technology maturation and increased market certainty. In addition, cost savings can be made by increased future infrastructure sharing.

8.4. CCUS financial mechanisms

As CCUS is currently at an early stage as an operational industry, the potential financial mechanisms between the high-purity CO_2 source industry and CO_2-EOR operator are unclear. This discussion attempts to elucidate some of the potential mechanisms but it is possible that alternative strategies might emerge in future. Contractual arrangements between the industries are likely to be based on quantified CO_2 delivery. For point-to-point projects with lower technical risks than cluster based approaches, take-or-pay and send-or-pay mechanisms, which are often used in the energy industry, seem likely to be appropriate financial mechanisms.

Under the ‘take-or-pay’ structure, the EOR operator is obligated to pay for CO_2 based on expected and agreed volumes, even if this amount is not drawn for the pipeline and used in operations. The ‘send-or-pay’ mechanism is similar however the responsibility falls on the high-purity CO_2 source industry – if they do not send agreed quantities of CO_2 they would be liable to pay a penalty. It is also likely under this system that deliveries of CO_2 over and above the agreed quotas would also trigger some payment between the entities. This system exposes the industries directly to their own operation risks and therefore provides the greatest incentive for the parties to manage these [14]. However, it also creates the greatest revenue uncertainty for the entities.

Another potential CCUS financial mechanism is a ‘Fully Integrated Contract’ – where all the partners invest in a joint venture to own and operate the project and receive the same rate of return on their investment [15]. Under this model each participant will receive the same return regardless of whether operational problems stem from their part of the process.

It might be more appropriate to pay transport network operators on a more basic model of the amount of CO_2 they transport. Contracts in the oil and gas industry are often arranged in this way.

The mechanisms highlight the risks borne by each of the entities, which are likely to become more complicated as multiple source and sink industries join onto networks. Reaching agreement on contractual arrangements could prove to be a significant challenge because different entities may require different rates of return. With regards to a demonstration project, the government should take into consideration the financial risks involved by each in the applied financial mechanism when allocating investment funds.

8.5. Management of fluctuations and interruptions

A major constraint to the operation of the CCUS chain is the ability to cover fluctuations and interruptions. If one part of the CCUS chain for whatever reason ceases to function, depending on the financial mechanism in place, it may need to compensate all members of the chain – this would also apply when regulatory regimes exist that aim to mitigate CO_2, e.g., if the CO_2 source industry would be penalised by a regulatory body for not sequestering CO_2.

These issues are significant for EOR operators, which due to geological uncertainty can be deemed to have the highest technical risk. A potential way to mitigate this problem would be where all elements of the CCUS chain were controlled by a single entity. However, this still would not alleviate the risk of losses if any part of the chain stopped functioning. It will be difficult to attract investment for CCUS unless the government will be able to share some of the financial risks associated to potential technical problems for CO_2-EOR.

9 Recommendations

In summary, the material presented in this study suggests that:

- There are four identified viable early opportunities in Shaanxi province, which use high purity CO_2 captured from methanol plants to be applied for CO_2-EOR in Yanchang Oilfields near Yanan and Changqing Oilfields near Yulin.

- Further technical analysis is required on a site-by-site basis to confirm the technical viability of each proposed CCUS demonstration -project e.g. geological surveys.

- The Chinese Government should continue to support a demonstration project in Shaanxi Province and coordinate interested industries. National funds should be provided to support the development of CCUS infrastructure and international funds sought. International cooperation on CCS technologies should be strengthened.

- The Ministry of Science and Technology should continue to support research and development on CCS. This would help to fill remaining technical gaps and overcome technical barriers to the implementation of CCUS. A vehicle to achieve further R&D breakthroughs could be the formation of national low carbon research centre to strengthen links between academia and industry.

- The Chinese Government should build a regulatory and policy framework for CCUS, drawing on the experiences of other countries, and consider the issue of management of risks due to the breakdown of elements in the CCUS chain when allocating funds for projects. This could be used to develop a standardised approach, which could be replicated for future CCUS projects.

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ABOUT US

The Centre for Low Carbon Futures is a collaborative membership organisation that focuses on sustainability for competitive advantage. Founded by the Universities of Hull, Leeds, Sheffield and York, the Centre brings together multidisciplinary and evidence-based research to both inform policy making and to demonstrate low carbon innovations. Our research themes are Smart Infrastructure, Energy Systems and the Circular Economy. Our activities are focused on the needs of business in both the demonstration of innovation and the associated skills development. Registered in the UK at Companies House 29th September 2009 Company No: 7033134.

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