Project N° 038966

COACH

Cooperation Action within CCS China-EU

Executive Report

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The COACH project was launched on November 1st 2006 for a period of 3 years, as part of the 6th framework programme of the European Commission which partly funded its activity.

Gathering 20 partners comprising 8 Chinese partners and 12 European partners, the COACH project was conceived as contributing to the first phase of the Near Zero Emission Coal fired power plants (NZEC) programme, a 3 phase programme developed between the European Union and China and aiming at combating climate change by enabling the deployment in China of thermal power plants equipped with CO_2 capture and storage (CCS) facilities.

The objective of the COACH project was thus to establish the basis of a future CCS demonstration operated on an Integrated Gasification Combined Cycle (IGCC) thermal power plant, with a subsequent storage of CO_2 in either mature hydrocarbon reservoirs, deep saline formations or unmineable coal seams.

The COACH project consisted of three main activities:

1. *the first one which received a very valuable additional financial support from the French Agency for Development (AFD), here gratefully acknowledged, was aimed at enabling the sharing of knowledge between European and Chinese COACH partners and developing capacity building,*
2. *the second one was to perform*
    a. *a detailed analysis of technologies to be used for implementing an option for CO_2 capture in an IGCC process with provision for production of electricity and chemical products and a cost analysis of both CO_2 capture and transport;*
    b. *an inventory of the emission sources, a quantitative assessment of the potential storage sites (the Dagang and Shengli oil provinces, the deep saline aquifers near by and the Kailuan coal mining area) located in the part of the Bohai basin in and near the Shandong province, and to finish with a mapping of the possible transport infrastructure that could be developed to connect CO_2 sources to CO_2 sites involving transport by pipelines or ship;*
3. *the third one aimed at integrating results obtained in the two previous tasks and come up with CCS scenarios that could be used for designing a CCS demonstration, including technical recommendations and cost analysis.*

This report summarizes the main achievements obtained in the COACH project, coordinated by Dr Francois Kalaydjian, IFP, France

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*The French Agency for Development (**AFD**) is gratefully acknowledged for its financial support to the dissemination, knowledge sharing and capacity building activities developed in COACH*

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1. General presentation of the project

1.1. Objectives

The objective of the COACH project was to initiate a strong and durable cooperation between Europe and China in the domain of clean coal-based power generation to respond to the fast growing energy demand of China while reducing its impact on the climate. Taking advantage of the combination of European and Chinese technologies, the COACH project was conceived as a first step preparing the ground for enabling the implementation of large-scale polygeneration energy power generation facilities including options for coal based electric power generation including the production of synthetic fuels and provisions for heat integration with surrounding industries. In this endeavour CO_2 capture and permanent geological storage - including use for enhanced oil or gas recovery - constitute an inherent and decisive prerequisite of the project. Though technically feasible, the associated production of hydrogen and its further utilization was decided to not be addressed in the project.

COACH has dealt with three techno-economic issues: (1) coal gasification for appropriate coal-based polygeneration schemes combined with CO_2 capture and storage; (2) identification of CO_2 emission sources of interest as well as reliable geological storage capabilities of CO_2 in the Bohai basin located in the Shandong province and schemes for transport infrastructure connecting sources to sinks; (3) legal, regulatory, funding and economic aspects.

In addition to that, COACH organised activities for contributing to the sharing of knowledge between China and Europe and the building of Chinese capacity.

To reach these objectives, COACH comprised 4 workpackages, co-led by European and Chinese partners addressing respectively, knowledge sharing and capacity building issues, identification of appropriate CO_2 capture and CO_2 storage technologies and then recommendations and guidelines for implementation.

1.2. Contractors involved

The COACH consortium has been established in order to assemble resources, skills and proficiency as well as industrial determination of leading European and Chinese institutions and companies covering all relevant disciplines required to carefully execute this project.

- **For Europe**, 12 partners were involved in the consortium :
  - 6 leading European enterprises (companies providing services, developing utilities as well as oil companies), namely
    - Services Petroliers Schlumberger (FR),
    - Alstom Power Ltd (UK),
    - Air Liquide (FR),
    - BP International Ltd (UK),
    - STATOILHYDRO (NO),
    - Shell International Renewables BV (CHN)
  - 5 RTD providers involved for many years both in various National programs and European funded projects related to capture, transport and storage of CO_2, namely
    - IFP (FR),
    - SINTEF Energiforskning AS (NO),
    - Geological Survey of Denmark and Greenland (DK),
    - Natural Environment Research Council – British Geological Survey (UK);
    - Kungliga Tekniska Högskolan (SE),
  - and one SME deeply involved in CCS research development:
    - ATANOR (FR)

- **For China**, 8 partners were involved in the consortium among which:
  - two companies :

    - RIPED, the Research Institute of Petroleum Exploration & Development – Langfang, attached to the Chinese oil company PETROCHINA
    - Greengen Ltd
  - five RTD providers, namely:
    - Tsinghua University
    - Zhejiang University
    - Institute of Engineering Thermophysics of the Chinese Academy of Sciences
    - Thermal Power Research Institute
    - Institute of Geology and Geophysics of the Chinese Academy of Sciences
  - and one partner representing public authorities, namely:
    - The Administrative Centre for China's Agenda 21

1.3. Main tasks

The COACH project was meant to be the first phase of a three-phase programme that should lead to a CO_2 capture, transport and storage (CCS) demonstration in China, the CO_2 being captured from an Integrated Gasification Combined Cycle (IGCC) coal power plant and then transported and stored deep in the underground in an appropriate geological setting – deep saline formation, mature oil field or unexploitable coal seams.

As of its final completion on the 30th of October 2009, after three years of work, the COACH project has contributed to :

- increasing the capacity building and disseminating the knowledge on CCS in China by organising the knowledge transfer between European and Chinese partners through workshops, conferences, stays of scientists both in Europe and in China, organisation of training sessions, publication of articles in scientific and professional journals and organisation of two one-week CCS schools gathering in total more than one hundred students, two thirds coming from China and the remaining from Europe thus enabling a cross-fertilisation between Chinese and European students featuring the next generation of scientists;
- assessing the optimal technologies to be used for implementing CO_2 capture in an IGCC based coal power plant;
- improving the understanding of the CO_2 storage potential in China in aquifers, mature hydrocarbon reservoirs and unexploitable coal seams by developing assessment methodologies and providing an estimate of the storage potential in a section of the Bohai basin
- mapping CO_2 transport infrastructure for connecting CO_2 sources of interest to most appropriate CO_2 geological sites
- reviewing the legal aspect and addressing the regulatory framework needed to deploy CCS in China
- identifying a couple of suitable cases, providing recommendations and guidelines on the methodologies and technologies that would need to be used for performing a CCS demonstration involving CO_2 capture from a coal power plant and CO_2 storage in an appropriate geological setting, assessing its feasibility and providing input for the design of such an operation.

The main results achieved in the COACH project are presented in the following sections.

2. Knowledge Sharing and Capacity Building

To tackle the issue of sharing knowledge and building capacity, the project assigned to itself three tasks:

- organising workshops
- enhancing information exchange and dissemination of results
- organising mobility schemes and education

2.1. Highlights

An important activity was deployed to perform an efficient knowledge sharing within the project. As such several workshops were organised both in China and in Europe, several sometimes in conjunction with companion projects such as UK-China NZEC, StraCO2, GeoCapacity.
In addition to the website created to exchange information between partners, a public website www.co2-coach.com was created.
A survey of CCS activities in both China and Europe was carried out and updated during the project.
To promote the work performed within the project, 9 presentations at international conferences, 5 papers were accepted for publication in international journals, 3 books were edited referring to the COACH project, 1 presentation of the COACH project was published in the European Parliament Magazine and several interventions in radio broadcasts were organised.
Regarding capacity building, in addition to the training sessions and workshops organised, two one-week long Schools were set up, one in April 2009 in Hangzhou and the other in October 2009 in Beijing. These two Schools attracted in total 80 Chinese students and 30 European students.

2.2. Organisation of workshops

Three plenary COACH workshops were organised alternatively in China and Europe: in Beijing on November 2006, in Rueil-Malmaison (France) during January 2008 and again in Beijing during March 2009 Other workshops gathering project partners and also students and academics took place in China (Xi'an, Hangzhou and Beijing).

In addition to that, BGS organised a common workshop to the UK NZEC project, the EU FP6 GeoCapacity project and COACH in Nottingham on February 10-12th 2009. This workshop drew together over 40 representatives from the Chinese academic community, European geological storage experts and policy makers to discuss geological storage in China. This workshop was supported by the French Agency for Development (AFD) through the COACH project and the UK Department of the Environment and Climate Change (DECC) through the UK-China NZEC project.

Other workshops were organised jointly with other related projects:

- Common GeoCapacity and COACH storage workshop in Beijing on 23-24th Nov. 2006,
- Common COACH, UK-China NZEC and GeoCapacity storage workshop in DongYing on 1st-4th July 2008,
- Joint COACH and STRACO2 workshop on CCS Regulation in Beijing on 18-19th March 2009,
- Conference on GeoCapacity results and the future for geological storage of CO_2, Copenhagen, 21-22nd October 2009,
- Common workshop between COACH, UK-China NZEC, STRACO2 and GeoCapacity in Beijing on 28-29th October, 2009.

2.3. Information exchange and dissemination

Figure 2-1: COACH Logo

A logo (see **Figure 2-1**) has been designed to illustrate the willingness of developing a tight cooperation between Europe and China on climate change issues. The issue of climate change is clear enough since in COACH, "CO_2" can be easily read. Europe is symbolised by the blue background, the yellow letters and the stars. China is symbolised by the Chinese characters right in the middle of the logo. The cooperation is illustrated first by the intersection of roman and Chinese characters and by the fact that the Chinese characters mean "cooperation".

A collaborative website created within the first year of the project was used to exchange data and information between the partners.

During the second year of the project a public website has been also created. Its address is the following: http://www.co2-coach.com/

A survey of CCS activities developed in Europe and China has been completed by ACCA21, ATANOR and IFP. Two reports were edited: a first report covering the 2007-2008 period was issued on September 2008 and an update covering 2008-2009 was issued on October 2009.

Many new CCS projects were launched during the last period covered by this second report, R&D type projects as well as industrial projects, thus confirming the increasing importance of CCS within China as well as in Europe.

COACH members have presented results of the COACH project at several International Conferences thus promoting the activity developed between the partners:

- the *3rd International Green Energy Conference* (*IGEC-3)* held in Sweden on June 15-18th, 2007,
- the *4th Tondheim Conference* on CCS held in Norway on October 16-17th, 2007,
- the *Energy Technology and Climate Change Research Workshop* held in Guangzhou, China on March 6-7th, 2008,
- the *Forum on Climate Change and Science and Technology Innovation* organised in Beijing during April 2008,
- the EU-China workshop on *Co-operation on Coal Value Chain Efficiency* organised in Beijing on October 17th, 2008,
- the *4th International Green Energy Conference* (*IGEC-3)* held in Beijing on October 19th-23rd, 2008,
- the *GHGT-9 Conference* held in Washington on November 17-20th, 2008,
- the *CCS European Conference* held in Oslo on February 10-11th, 2009,
- the *5th Trondheim Conference on CCS* held in Norway on June 16-17th, 2009.

Several papers were accepted for publication:

- Hetland, J.; Anantharaman, R.: "Carbon capture and storage (CCS) options for co-production of electricity and synthetic fuels from indigenous coal in an Indian context". Energy for Sustainable Development 13 (2009), Pages 56–63.
- Li H.; Yan J.: "Impacts of equations of state (EOS) and impurities on the volume calculation of CO_2 mixtures in the applications of CO_2 capture and storage (CCS) processes". Applied Energy, 2009, 86 (12), Pages 2760-2770.
- Li H.; Yan J.; and Anheden M.: "Impurity Impacts on Purification Process in Oxy-Fuel Combustion Based CCS system", Applied Energy, 2009, 86 (2), Pages 202-213.
- Hetland, J., Li Z., and Xu S.: "How polygeneration schemes may develop under an advanced clean fossil fuel strategy under a joint sino-European initiative", Applied Energy, 2009, 86 (2), Pages 219-229.
- Li, H. and Yan, J.: "Evaluating Cubic Equations of State for Calculation of Vapor-Liquid Equilibrium of CO_2 and CO_2 Mixtures for CO_2 Capture and Storage Processes", Applied Energy, 2009, 86 (6), Pages 826-836.

- Vincent, C.J., Dai, S., Chen, W., Zeng, R., Ding, G., Xu, R., Vangkilde-Pedersen, T. and Dalhoff, F., 2009, GHGT9 Carbon dioxide storage options for the COACH project in the Bohai Basin, China, Energy Procedia **1**, Pages 2785-2792.

Three books made reference to the COACH Project:

- a book (written in French) entitled *"La nouvelle donne du charbon"*, Ed. Technip authored by F. Kalaydjian (IFP) and S. Cornot-Gandolphe (ATIC services), English version to follow end of 2009;
- a book (written in French) entitled *"Le captage du CO_2"*, Ed. Technip authored by F. Lecomte, P. Broutin, E. Lebas (IFP).
- a book compiled by GreenGen about climate change and CCS.

A full page of information presenting the COACH results was also published in "The Parliament Magazine" in October 2009. This dissemination was realised with the financial support of AFD.

2.4. Mobility scheme and education

Exchange of scientific personal was organised. Some of the mobility actions are presented hereafter:

- Dr. Teng Fei (Tsinghua University –TU-) attended the GeoCapacity project meeting held in Athens in March 2007 and learned from other countries' progress for storage capacity potential assessment.
- Three TU representatives, Dr. Xu Ruina, Mr. Liujia, and Mr. Chen Jiyong, successfully applied and gained financial support to attend the International Summer School on CCS launched by the International Energy Agency (IEA) which was held in Kloster Seeon, Germany on August 2007.
- Arrangements were made for to enable the visit of Mr. Liu Lianbo (TPRI) to the SINTEF membrane laboratory in Trondheim for three weeks in August 07.
- A PhD student from IET visited Sweden (KTH) for 2 months in 2008 for a study on the simulation of polygeneration system.
- Prof. J. Yan (KTH) paid a visit in 2008 to IET, China.
- A training session on the Geographical Information System (GIS) used within the COACH project was delivered by BGS to the Tsinghua University (June 17–20th 2008).
- Training in reservoir modelling and simulation at GEUS: 2 post docs Liu Tong-jing and Zhao Chuan-feng from the China University of Petroleum (Beijing) stayed in Denmark for one month in September 2009. During that stay they carried out a study related to the dynamic modeling of CO_2 storage in a saline formation and comprising a discussion of the impact of petrophysical parameters such as capillary pressure and relative permeabilities.

Two one-week long Schools gathering Chinese and European students were organised in China with the support of AFD. A Spring School took place in Hangzhou in April 2009 (see **Figure 2-2**) and an Autumn school in Beijing during October 2009.

Figure 2-2: Group of Students and Teachers during the first school in Hangzhou

3. Capture technologies

3.1. Highlights

A generic IGCC concept implemented with CO_2 capture has been defined and compared against a plain IGCC based on the GreenGen Phase I system without CO_2 capture.
Benchmarking was made between a reference case for which a gas turbine burns a low-calorific syngas and a base case consisting of a turbine burning a hydrogen enriched gas mixture diluted with nitrogen. Provision for methanol production was made as well but was not reviewed in details.
The CO_2 capture cost was found to amount to €18/tCO_2 whereas the cost of the avoided CO_2 was a little bit higher amounting to €22/tCO_2.
CO_2 handling was also addressed for transporting and storing the CO_2 safely. Three cases were studied for transporting the CO_2 from the Tianjin power plant to the Shengli oilfield region, by rail, pipeline and ship.

3.2. Introduction

The main purpose of COACH is to pave the way for CCS in China. In pursuit of this, the developments made in COACH on *Capture Technologies* is a major driving force that acts through four specific tasks:

1) Inventory of power generation and optional carbon capture
2) Concept studies for coal-based plants with carbon capture in China
3) Potentiality studies of polygeneration schemes linked with coal-based plants in China
4) Recommendations for pre-conditioning of CO_2 for transfer from plant to storage site in China.

Inevitably, as CO_2 capture means using additional fuel and producing less electricity to sell at a higher price (cost of electricity, COE), CCS can hardly compete against conventional coal-based power cycles, unless a regulatory framework is in place that duly favours systems that emit almost no greenhouse gases. It is essential therefore that policy makers and regulators have some knowledge about the potential and the significance of real options: In this context a well-developed understanding is key – especially of the inventory of Chinese power stations and emerging CO_2 abatement strategies when planning new capacity (greenfields) or when considering retrofitting existing plants (replacement studies). This also holds true for power cycle studies and optional heat integration with surrounding industries to exchange waste heat if practical.

Modern Chinese plants - larger than 300 MW_e that have gone into operation after the year 2000 - have been targeted for identification. These plants have been subjected to assessment and screening on a typological basis for possible upgrading or for integration with a plausible capture technique.

It seems evident that coal gasification in particular is deemed to represent a promising technology for China. However, in order to pave the way for large-scale deployment of integrated gasification combined cycle schemes (IGCC) with multiple yields and with CCS, the reliability and availability must be improved, and likewise the capital and operational expenses should be reduced. This requires insight in optional technologies about coal gasification, syngas pre-treatment, air separation and various schemes for polygeneration as well as the pre-conditioning and transport of CO_2. Efforts have been made to assess promising schemes for co-production of electricity and synthetic fuels, whereof the latter is intended for the future transport sector in China such as hydrogen and synthetic gasoline.

Pursuant to emerging CO_2 capture techniques, China has decided to place efforts on coal-gasification partly because of the higher development potential of the IGCC and partly because gasification inherently leaves an option for polygeneration that also facilitates the capturing of CO_2. China is also paying interest in post-combustion capture via its Huaneng Group pilot in Beijing (3 ktpa, 2008) and the new demo unit in Shanghai scheduled to be operational in the end of 2009 (Huaneng, 100 ktpa).

In contrast to China, however, Europe aims at having up to 10-12 large CCS demonstrations operable on European soil by 2015-2020. These demonstration projects are required to verify the major capture routes (pre-combustion, post-combustion, oxy-combustion and various storage options).

3.3. Assessments and findings

Seemingly, the flagship of China is the GreenGen demonstration project (Phase 1, 250 MW_e), which is an autonomous IGCC demonstration scheduled to become operational in 2011. The GreenGen will further evolve through two consecutive phases into a larger unit with CCS by 2015 (400 MW_e). The strategic importance of the IGCC is that it may lessen China's dependency of imported petroleum (oil and gas). This is due to the ability of polygeneration schemes to co-produce synthetic liquid fuels and gas, chemicals and electricity from indigenous coal (refer to **Figure 3-1**).

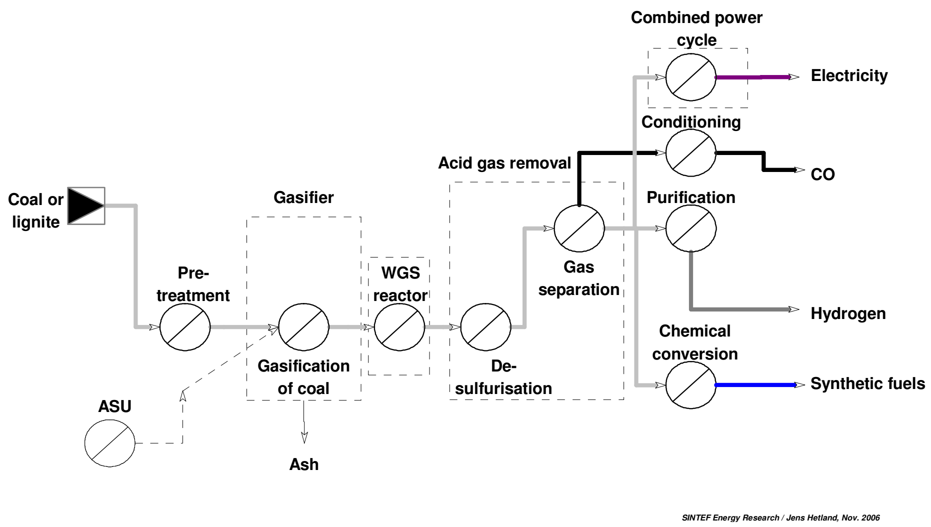

Figure 3-1: Generalised polygeneration scheme

3.3.1. Power cycle

A generic IGCC concept that employs CO_2 capture (i.e. IGCC-CCS) has been defined and compared against a plain IGCC (similar to GreenGen Phase 1 without CO_2 capture). Both cases are tied to the regulated price of electricity in China, assumed to correspond to conventional coal-based power generation.

Definition of the two cases was made according to preferences raised by Chinese partners of using a generalised IGCC scheme (refer to **Figure 3-2** and **Figure 3-3**). Both cases are made up by an oxygen-blown gasifier dry-fed with pulverised coal, and a down-stream combined power cycle. The power island comprises the gas turbine, the heat recovery steam generator, the steam turbine, compression of nitrogen for dilution in the combustor, injection of steam and condensation of steam.

Whereas the reference case uses a gas turbine that burns a low-calorific syngas and with no further gas cleaning than a conventional IGCC, the base case is made up by a generic gas turbine fuelled with a hydrogen-rich gas mixture that is diluted with nitrogen, and with a pre-combustion capture process that removes (and stores) about 90% of the CO_2. It furthermore includes a compression system that leaves the captured CO_2 in dehydrated and dense phase at pipeline pressure (selected to be 110 bar).

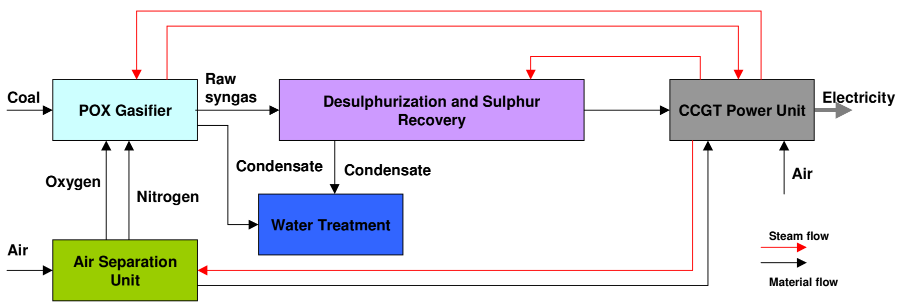

Figure 3-2: Reference case – electricity production without CO_2 capture

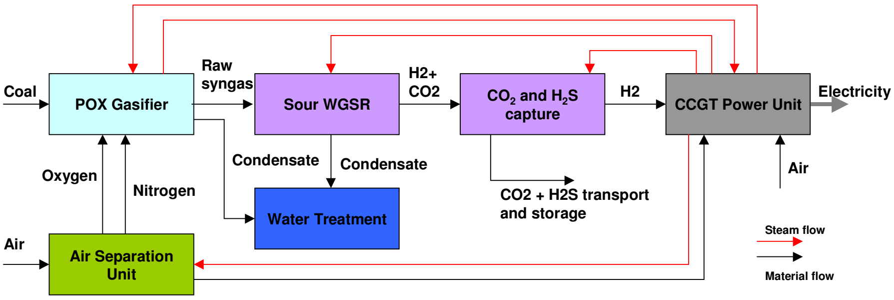

Figure 3-3: Base case – electricity production with CO_2 capture

Available technologies, including the production of hydrogen, ammonia, methanol, DME, and diesel have also been addressed, although they were not reviewed in detail for integration with these schemes.

3.3.2. Benchmarking

The benchmarking was made under a subset of prerequisites specific to China[1]. In **Figure 3-4** the cost of electricity (COE) is presented on relative terms using as reference the prevalent price of electricity in China (i.e. 0.327 RMB/kWh as of summer 2009). At the current state-of-the-art development the COE of an IGCC is expected to be almost 20% higher than the market price. Additionally, the inclusion of CCS will add another 2/3 of the COE of the IGCC (GreenGen Phase 1). However, the availability of the plant is an important factor, and it should be a target to develop the system for at least 7500 operating hours per year – in line with European IGCC projects.

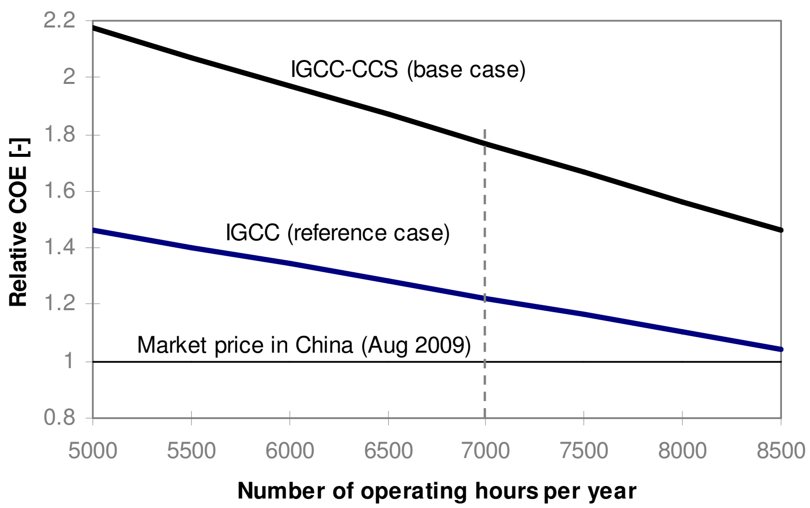

Figure 3-4: Cost of electricy (COE) versus the number of operating hours per year. (Linear approximation is based on estimates of the COE at 5000 hours and 7000 hours.)

[1] Construction time: 4 years, repayment time: 15 years, working time: 20 years, interest rate: 7.83%, electric price: 0.327 RMB/kWh, working hours per year: 7000 hours (and 5000 hours for reference and scaling).

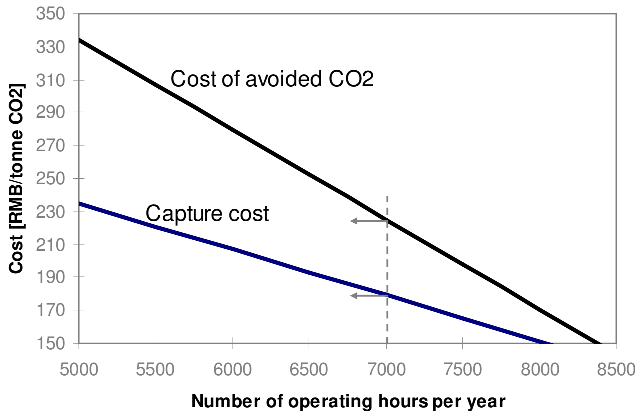

Figure 3-5: Capture cost and cost of avoided CO2 versus number of operating hours of the plant per year. (Linear approximation is based on estimated cost at 5000 hours and 7000 hrs)

Following these findings, the capture cost and the cost of avoided CO_2 are presented in **Figure 3-5**. As shown the **capture cost amounts to almost 180 RMB/tCO_2** (roughly 18 Euro/tCO_2) and **the cost of avoided CO_2 is somewhat higher: 225 RMB/tCO_2** (roughly 22 Euro/tCO_2).

3.3.3. Improvements, risk assessment and standards

Further impacts of CCS are also addressed, and the needs and the potential for further improvements have been identified along with a preliminary risk assessment. As IGCC is a rather complex and largely integrated concept, safe and robust operation has been assessed using a Failure Modes, Effects and Criticality Analysis (FMECA) on a full 'polygeneration' cycle including methanol and electricity production via coal gasification with CO_2 capture.

Additionally, the properties of Chinese coals have been investigated and representative coal data have been collected and systemised. In addition, considering the importance of normative aspects, the standards and codes of the International Standardisation Organization (ISO), and the International Electrotechnical Commission (IEC) and corresponding Chinese standards and codes regarding hydrogen energy and the handling and usage thereof have been identified on an open basis in China and in Europe.

3.3.4. CO_2 handling

In order to dispose of the CO_2 in a stable sink – either in geological formations or for making additional use of the CO_2 for EOR/EGR (enhanced oil recovery / enhanced gas recovery) the necessity of CO_2 pre-treatment has been duly addressed. The pre-requisites and conditions are reflected in a sub-set of requirements pertaining to the down-stream gas transfer and storage systems relating to future carbon capture plants in China. This includes mechanical and metallurgical integrity of the CO_2-handling system to avoid corrosion that eventually may lead to gradual or abrupt leakages, and further thresholds for possible impurities in compliance with HSE requirements for safe transport and also for stable storage conditions.

Pressure and temperature are important criteria in the handling of CO_2, in particular if the CO_2 has to be piped or transported in tanks over some distance, which usually requires that the CO_2 is transformed into a dense phase (either cryogenically or supercritically).

In order to assess the tail-end impacts of the CCS concept, a case-based study was conducted along three alternative routes, all taking delivery from the CO_2 that is captured from the GreenGen demonstrator in Tianjin (shown as R1 in **Figure 3-6**) to the storage site in the Shengli oilfield province (Point B).

The three alternatives are:

1) The pipeline route,
2) the ship route, and
3) the railway route.

For the two latter routes cryogenic conditions were used at a meso pressure (around 8-10 bar), whereas a pressure of 110 bar was assumed for the pipeline.

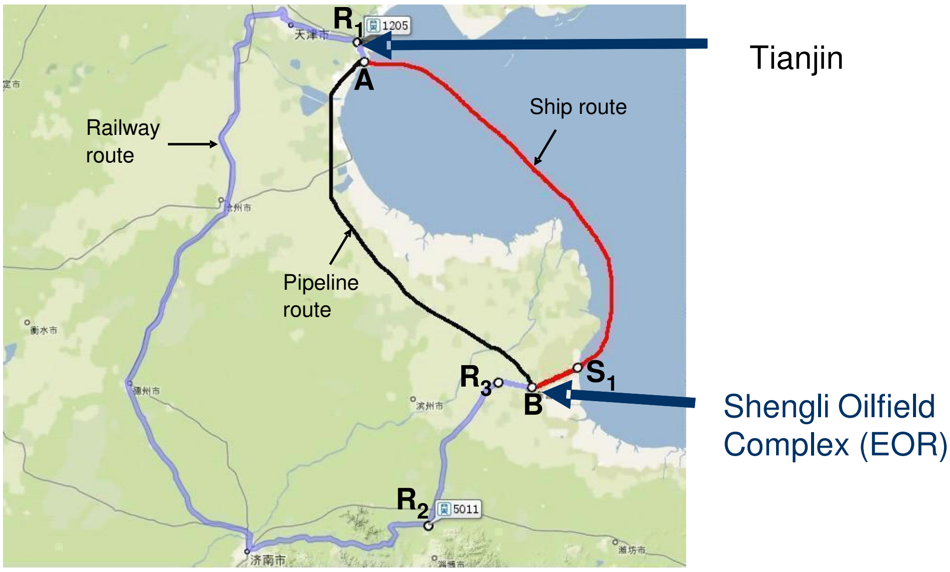

Figure 3-6: CO_2 transport cases linking the GreenGen plant (R1) to the Shengli Oilfield Complex (B) via pipeline, by ship or by railway.

4. Geological storage and large scale use of CO2

4.1. Highlights

Potential CO_2 storage sites have been investigated in the part of the Bohai Basin located in and near the Shandong province, East China. Selected oilfields, saline aquifers and unmineable coal beds were considered. Possible test sites are available in some of the oil fields.

- ***The coals of Kailuan mining area have a high ability to adsorb CO_2, but the CO_2 injection rate is anticipated to be low. Enhanced coalbed methane recovery could be considered.***
- ***The aquifers show a large storage potential, but further geological investigation is required.***
- ***Some of the oilfields may be suitable for an enhanced oil recovery pilot. Injecting CO_2 into an mature oil reservoir cannot only store CO_2, but also enhance the oil recovery.***

The storage potential in oil fields is however much smaller (10–500 Mt) than in the saline aquifers (around 20 Gt).

Three tasks were carried out :

- Task 1: Capacity estimate at regional level
- Task 2: Mapping of the geology and point emission sources
- Task 3: Improving methodologies for storage capacity assessment and site selection criteria

GEUS and Tsinghua University had joint co-leadership of the three tasks.

For Task 1 the Institute for Geology and Geophysics (IGGCAS) was responsible, working in cooperation with Tsinghua University (3E), Research Institute of Petroleum Exploration and Development PetroChina (RIPED), China University of Mining and Technology, GEUS and BGS. Consultations were made during the project with industry partners including BP, Statoil, Shell China E&P, Schlumberger (EPS).

For Task 2 BGS was responsible for this task, working closely with Tsinghua University, Institute for Geology and Geophysics and also with support from GEUS.

For Task 3 GEUS and Tsinghua University were jointly the overall responsible partners for this task working closely with all other partners.

4.2. Task 1: Capacity estimate at regional level

The results of Task 1 are described in detail in technical report D3.1 Assessment of CO_2 storage potential of the Dagang and Shengli oilfield provinces, Jiyang Depression and Kailuan mining area, and the D3.1 Appendix COACH project Dagang oilfield province; summary of geological storage assessment.

The aim of this task was to assess the CO2 storage potential of oilfields, deep saline aquifers, and coals. The potential of enhanced oil recovery (EOR) by CO2 injection was also assessed.

Storage potential of selected sites in the Bohai Basin (north-east China) has been evaluated by Chinese scientists using published data with support from EU partners. Most industrial development and therefore the majority of large sources of carbon dioxide (CO2), lie along the eastern coastline and consequently storage sites are being sought in this area. The storage sites considered were the Dagang oilfield province (Tianjin Municipality), Shengli oilfield province (Shandong Province), Kailuan mining area (Hebei Province) and deep saline aquifers in the Jiyang Depression (Shandong Province) (see **Figure 4-1**).

Enhanced oil recovery and security of energy supply are key considerations for China. Investigation into potential storage capacity was carried out for the Dagang and Shengli oilfields and enhanced oil recovery (EOR) was evaluated for selected Shengli oilfields. A CSLF-based methodology (Bachu et al., 2007) was applied to evaluate storage potential of the Dagang and Shengli oilfields. The Shengli oilfield province was also evaluated using a model created by the China University of Petroleum (CUP) Beijing based on dissolution of CO_2 into pore water and oil.

Using data provided by the Research Institute of Petroleum (PETROCHINA), the overall **storage potential** of the seven selected fields in the **Dagang oilfield province was estimated at about 22 Mt**, of these fields, the Gangdong Oilfield had the largest estimated storage potential of 10 Mt CO_2 in the Guantao Formation. Average porosity and permeability of the sandstone reservoirs in the Gangdong Oilfield are 31% and 975 mD respectively.

The storage potential of selected fields in the **Shengli oilfield province was estimated to be 472 Mt** using the CSLF-based methodology and up to 463 Mt using the CUP Beijing (CUPB) methodology depending on remaining oil reserves in the oilfields, as the most recent publicly available data are from 2000. These oil reserves generally lie below 1000 m. The Shengtui Oilfield was calculated to have the greatest potential storage capacity; 186 Mt using CSLF-based methodology and 117 Mt using the CUP Beijing model. Average porosity of the reservoirs in of the fields evaluated is 31%. Data for the Gudong Oilfield indicated porosity of 28 – 35% and permeability of 510 – 3118 mD (Zhang et al., 2004, C&C reservoirs, 1998) in the Guantao Formation.

The potential for recovering additional oil from the Shengli oilfield province was also investigated. **The additional oil which could be recovered by EOR was calculated to be approximately 23 – 112 Mt** using recovery rates of 2 – 10%.

Kailuan mining area lies in the north Bohai Basin. It contains 3750 Mt of coal reserves of Carboniferous and Permian age mostly lying at depths greater than 1000 m. Storage and enhanced coalbed methane recovery were considered. As Kailuan is an active coal-mining area, CO_2-ECBM could only be applied at selected sites where there is no risk of damaging the future energy resource or leakage through contact with future, active or abandoned coal mines. Site screening determined that uneconomic seams are present at suitable depth for CO_2 storage.

Experiments were carried out by the China University of Mining and Technology on coals from Majiagou Mine and Linnancang Mine. These coals are considered to be representative of coals from this mining area and so were used to imply properties for deeper, unmineable coals. The samples were subjected to isothermal adsorption experiments and proximate analysis (moisture, ash and volatile matter, sulphur content and vitrinite reflectance were determined). The maceral compositions were determined to be favourable for CO_2 adsorption. Comparison of three different theoretical methods for estimating adsorption was undertaken. This comparison demonstrated the importance of experimental results for calculating absorption properties and thereby for estimating CO_2 storage capacity.

Other coal samples from Kailuan mining area were also examined to determine porosity and permeability. These properties were determined to be generally low with the most favourable porosity and permeability found in the Early Permian Taiyuan Formation coals with porosity 3.7% and permeability 3.6 mD. Using a CSLF-based methodology (Bachu et al., 2007), **storage in all the coal seams in the Kailuan Mining Area was calculated to be 504 Gt; however, not all this capacity can be considered available for storage** as some of these seams may be mined in the future and permeability is generally low so not all the coal could be accessed.

The oil-bearing Jiyang Depression lies in the central Bohai Basin. It covers an area of around 20,000 km^2 and is subdivided into six sub-basins. Through initial site screening, the Neogene aquifers and in particular the Guantao Formation were determined to show the most promise; they lie at suitable depth (greater than 1000 m), have a broad areal distribution and good connectivity between fault blocks. After further site screening, the Huimin sub-basin basin within the Jiyang Depression was selected for further study. The Institute of Geology and Geophysics (Chinese Academy of Sciences) evaluated the potential for storage in this region. The Guantao Group comprises partially cemented and fractured gravel rocks overlain by thick mudstones of the Lower Minghuazhen Formation. Borehole information indicates groundwater flow from the margins towards the centre of the depression with stable pore-water chemistry. The Linfanjia and Shanghe oilfields in the Huimin sub-basin have average porosities of 31% and 19 % respectively and measured permeabilities of 390 mD and 11 – 150 mD. There is more uncertainty in estimation of aquifer storage potential as a result of limited data availability due to general lack of commercial interest in deep saline aquifers. Storage capacity for the Huimin sub-basin was estimated to be 22 Gt. However, further research is required to identify closed structures as targets for storage.

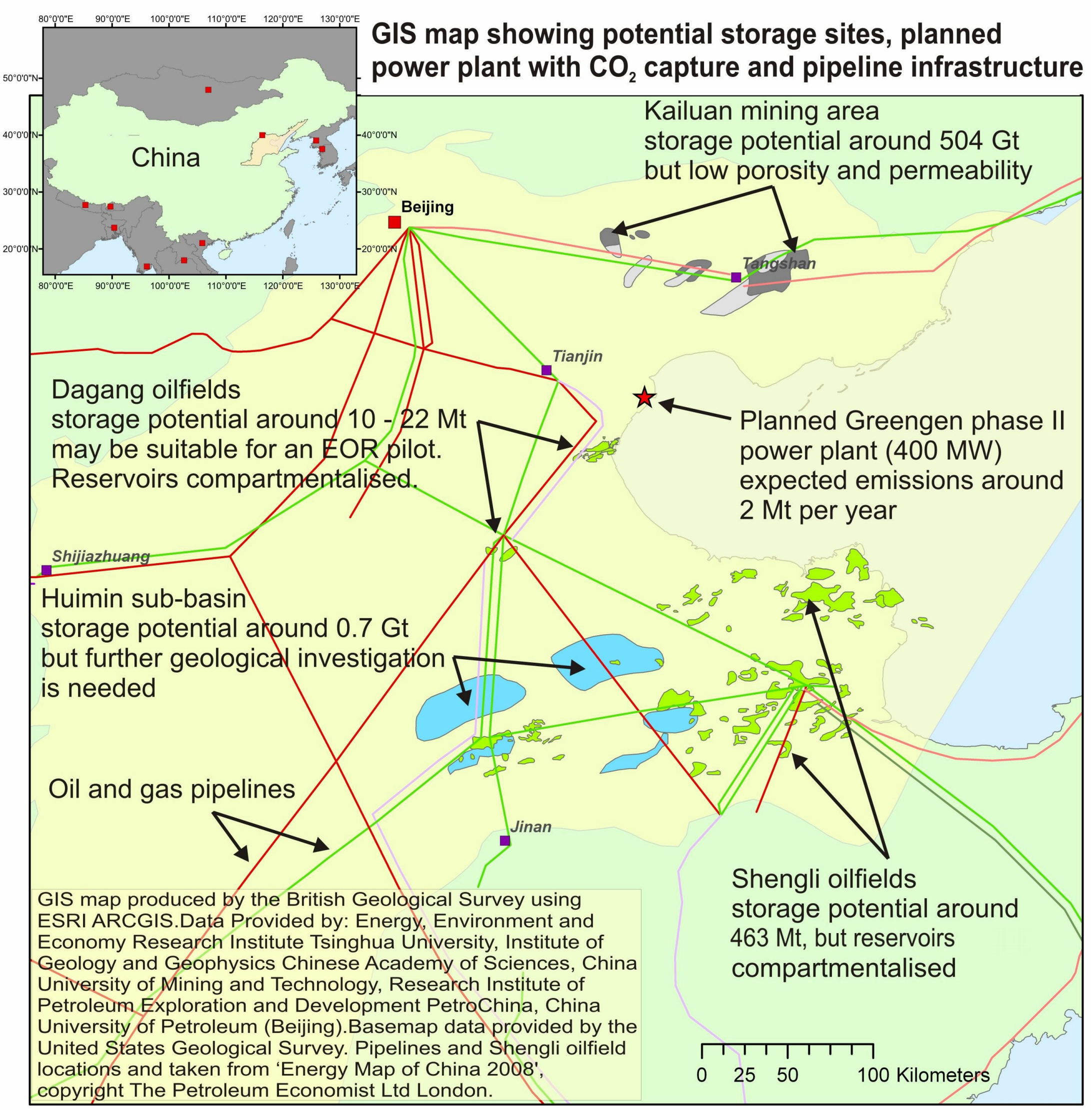

Figure 4-1 GIS map showing CO_2 sources, piping network and potential storage sites.

Based on storage site potentials evaluated by the COACH partners, it is considered that the capacity of the Dagang oilfield province is not sufficient for large-scale storage, though there is potential for a small scale pilot in storage or EOR pilots. The capacity is quite small and injection would be complicated by the structural and lithological variability of the reservoir. The Shengli oilfield province, located more centrally in the Bohai Basin was considered more promising. Storage potential in the Kailuan mining area is limited by permeability of the coals. On initial evaluation, the Guantao Formation in the Jiyang Depression has a large potential storage capacity, though this should be considered with caution as it does not have the benefit of proven ability to store buoyant fluids and less data are available for detailed evaluation of the storage potential.

4.3. Task 2: GIS mapping of the geology and point emission sources.

The results of Task 2 include the construction of the Geographical Information System (GIS) and project databases as well as a web-based version of the GIS. The results are further described in detail in the technical report D3.2 GIS mapping of Geology, Point Emissions Sources and Least Cost Paths.

The aim of this task was to produce inventories for CO_2 emissions, infrastructure and potential CO_2 sinks which were to be compiled into a Geographical Information System (GIS) and a web-based Geographical

Information System (webGIS). This involved collection of data in a specified fixed standard format so data could be readily input into the project GIS.

The objective of the COACH GIS and webGIS was to produce a Geographical Information System that would incorporate the wide range of data provided by the project partners and allow meaningful access to the data. The basic methodology for developing the GIS followed on from previous work carried out in China for the GeoCapacity project. The webGIS was developed to allow partner only access to users who do not have access to the ESRI ArcGIS software to access the project data (
Figure 4-2).

The project databases contain geological storage information, pipelines and point sources. Location maps of coalfields in Hebei Province as well as the locations of the Shengli and Dagang oilfield provinces have been georeferenced and digitised.

The storage capacity data in the databases were calculated using the CSLF method. The CUP storage capacity data for the Shengli oilfield province, based on the Tanaka et al. (1995), are also recorded. This ensures that all capacities in the main fields have been calculated using a uniform CSLF-based method.

The GIS allows users to simultaneously view one or more 'layers' of data including the location of the CO_2 sources and possible CO_2 sinks. It also enables the user to perform extensive onscreen analysis on all the available data as well as to produce thematic maps of the data.

Copyright information is also a feature of the GIS. Users must agree to abide by the copyright of the data before the GIS will open fully and there is also the ability to access the copyright information from within the GIS should users wish to read it again.

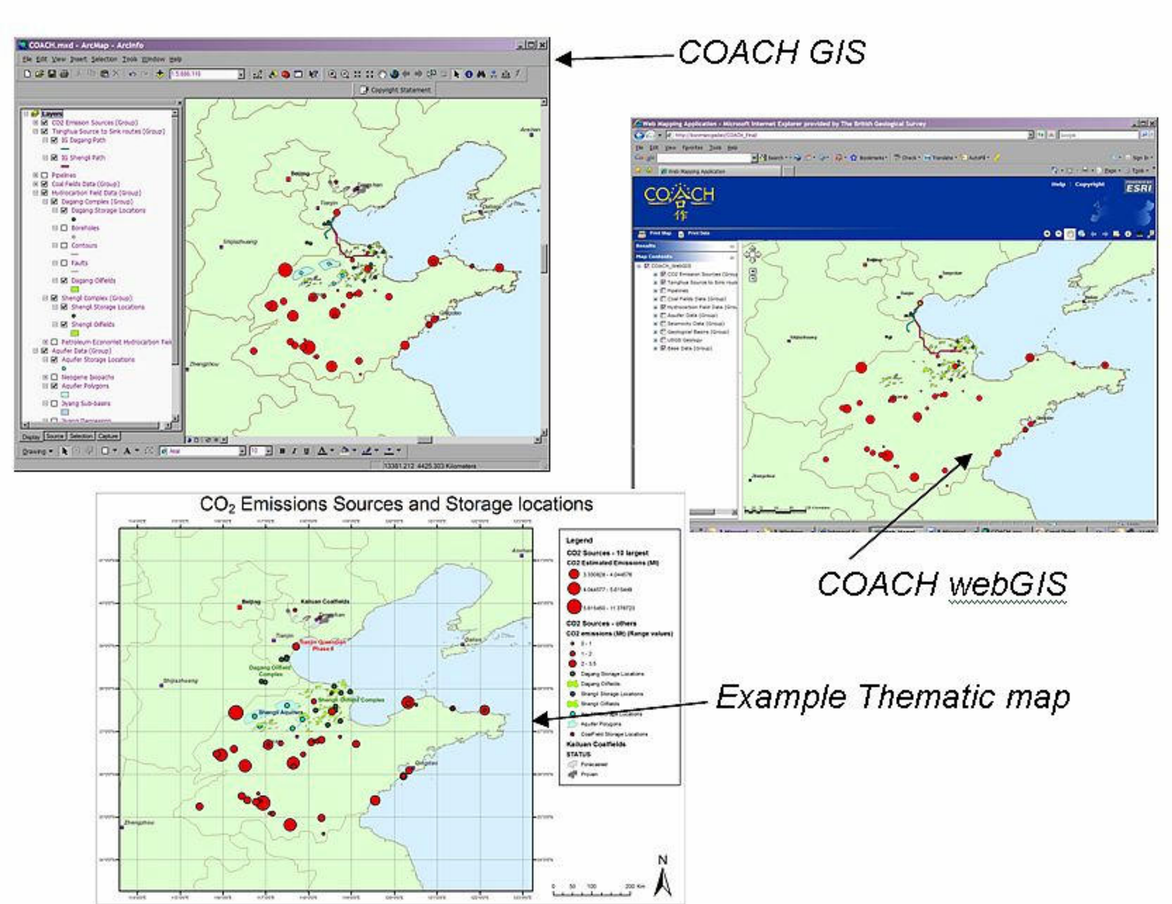

Figure 4-2 Diagram of the GIS, WebGIS, and an example thematic map

Part of the focus of this task has been on large stationary CO_2 sources, such as power plants, ammonia production plants, iron and steel production plants, cement kilns and oil refineries. The electricity generation and industrial sectors offer the best potential for large-scale, centralized capture of CO_2. The electricity sector is a prime candidate for CO_2 capture and the relevance of a CCS strategy for the electricity sector will increase in the coming years. The industry sectors, in particular the manufacturing sector for total global energy use and related environmental impacts, make it a second important category where CO_2 capture could be applied.

There are three oilfield provinces around the Tianjin IGCC power plant. They are Huabei, Dagang and Shengli oilfield provinces (**Figure 4-1** and **Figure 4-3**). Storage potential in the Huabei oilfield province, which was estimated in GeoCapacity project, is used alongside data gathered in this project to establish comparisons between different matching pathways for Tianjin IGCC power plant (Chen and Michel, 2009). Dagang oilfield province is the nearest potential storage site, but is not suitable for large-scale storage, though could be considered for EOR pilots. Therefore, as the distance between GreenGen IGCC power plant and Huabei and Shengli oilfields are similar, these two oilfield provinces were selected for the source and sink matching exercises (**Figure 4-1** and **Figure 4-3**).

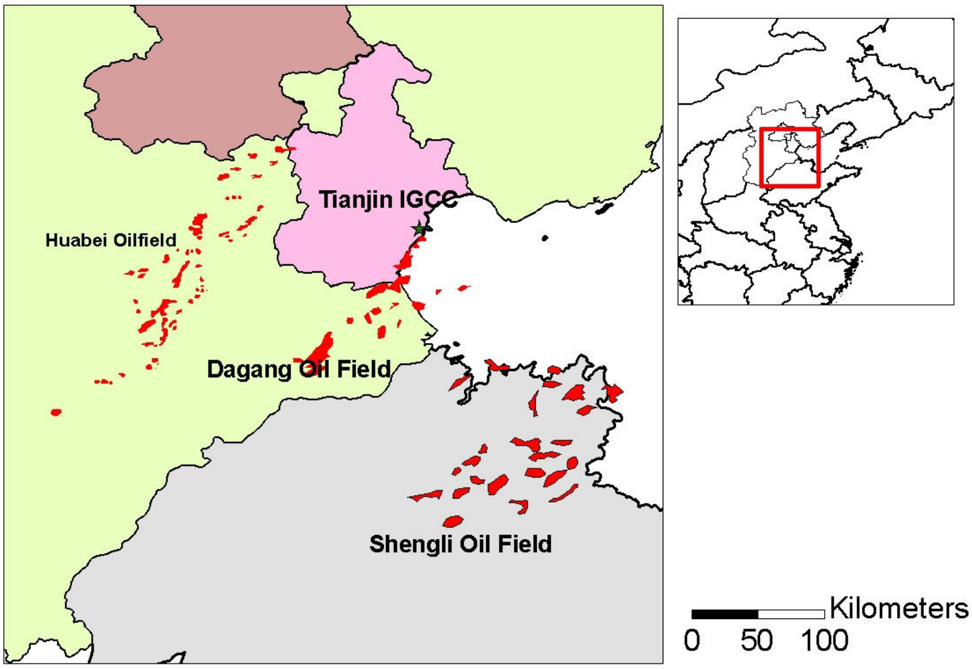

Figure 4-3 Location of GreenGen power plant and Huabei, Dagang and Shengli oilfield provinces

4.4. Task 3: Improving methodologies for storage capacity assessment and site selection criteria

The results of Task 3 are described in detail in technical reports D3.3 Improving methodologies for storage capacity assessment and site selection criteria, and in D3.3 Appendix Comparison of methodology for storage capacity assessment.

GEUS and Tsinghua University were jointly responsible overall for this task working closely with all other partners.

A standardized methodology for site selection criteria and methodologies for calculating storage capacity in different geological settings, aquifers, hydrocarbon and coal fields, is outlined in the D3.3 report. The work with establishing internationally recognised standards for capacity assessments was initiated by the Carbon Sequestration Leadership Forum (CSLF) about a year before the start of the GeoCapacity project and a CSLF Task Force has been active since. The paper "Estimation of CO_2 Storage Capacity in Geological Media - Phase 2" (Bachu et al., 2007) published by the CSLF presents comprehensive definitions, concepts and methodologies to be used in estimating CO2 storage capacity. Creation of a standardized methodology will ensure quality, consistency and comparability.

For a site being suitable for CO_2 storage some basic, geological related criteria has to be fulfilled.

- Sufficient depth of reservoir to ensure that CO_2 reach its supercritical dense phase but not so deep that permeability and porosity is too low.
- Integrity of seal to hinder CO_2 escape.
- Sufficient CO_2 storage capacity to hold the CO_2 expected to be released from the source.
- Effective petrophysical reservoir properties to ensure CO_2 injectivity to be economically viable and that sufficient CO_2 can be obtained.

Storage capacity assessment begins with identifying sedimentary basins. Once the suitable sedimentary basins in a region or country have been outlined the next step is to identify potential reservoir and sealing units for CO_2 storage and characterization of their geological and physical properties. At this point regional CO_2 storage estimates based on the bulk volume of aquifers can be calculated. More precise estimates can be provided if stratigraphic or structural traps with suitable reservoir and sealing properties are identified within the aquifers and the storage potential of the individual trap is calculated. Regional estimates can now be calculated as the sum of storage potential of all the traps identified.

Fulfilment of these basic criteria depends on the values of several geological and physical parameters. In the search for suitable sites for CO_2 storage it is therefore important to estimate if the basic criteria listed above and their associated geological and physical parameters are met. The first step in a site selection process is to screen sedimentary basins for CO_2 storage potential. The goal with the screening process is to identify predictable, laterally continuous, suitable permeable reservoir rocks overlain by potentially good quality caprocks at a suitable depth based on existing data. By screening an overview is obtained of those sites which are best described and best fulfil the storage criteria on the basis of existing data. The screening therefore narrows the search at an early stage so that costly and time-consuming supplementary investigations such as colleting and interpreting seismic data is confined to potentially prospective areas only.

The D3.3 Appendix deals with the difference methodologies, which have been used to calculate the CO_2 storage capacity in the Shengli oilfield province (D3.1 report, Zeng et al., 2009). The methodologies of CSLF and of Tanaka et al. (1995) are compared in this appendix.

4.5. Risk assessment and future work

The work that was carried out to study the geological storage of CO2 in the Bohai basin has been focussed on capacity, with some consideration given to the likely containment and injectivity risks though those aspects are addressed somewhat in the next section of this report (see Section 5. Integration and Recommendations).

Leakage risk may indeed in itself disqualify many depleted fields. Fault leakage risk may also disqualify many heavily faulted areas. Severe reservoir compartmentalization may result in a high injectivity risk as compartments are pressured up upon injection. A balanced discussion on the relative risks of the depleted oilfield, aquifer or coalfield storage options or the uncertainties due to lack of data cannot be avoided.

A future work program needs to be based on actual subsurface and production data from a few representative locations and should include:

- wellbore leakage assessment
- injectivity modelling - single well models with sensitivities on reservoir properties and continuity (to reflect likely high compartmentalization)
- geomechanics - study of the impact of compaction due to HC production in these high porosity unconsolidated sandstones and likely deterioration in reservoir properties for injection
- study of the potential impact of reactive chemistry between CO_2, brine and rock, which may cause near wellbore impairment
- seal continuity and quality studies
- fault leakage studies, including reactivation due to CO_2 injection
- modelling of likely lateral migration of the CO_2 plume
- estimates of potential well count based on vertical, deviated and/or horizontal wells

4.6. References

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- Zeng, R., Li M., Dai, S., Zhang, B., Ding, G.. and Vincent, C. J., D3.1: Assessment of CO_2 storage potential of the Dagang and Shengli oilfield provinces, Jiyang Depression and Kailuan mining area. 76 pp.

5. Integration and Recommendations

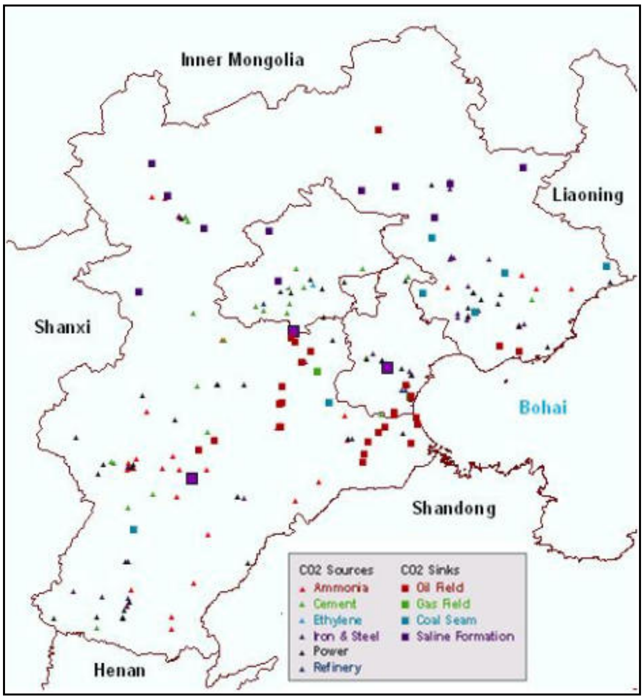
5.1. Highlights

Two scenarios have been designed to screen options for a possible CCS demonstration project. These have considered capture of CO_2 from the Tianjin IGCC power plant and storage in one or more geological formations in the Bohai Bay geological basin.
Storage for the smaller scale scenario (0.1 – 1 million tonnes/year) could be accommodated in the Dagang or Shengli oilfields. Storage for the larger scale scenario (2 – 3 million tonnes/year) could be accommodated in the Shengli oilfield province (in a number of fields) or potentially in the saline formations in the Huimin sub-basin area. For each of these options, a preliminary risk assessment was performed.
Furthermore, a thorough cost analysis was performed. This lead to an integrated CCS cost which was found to lie in the range €26-30/tCO_2.
Finally, policy and regulation issues were addressed.

5.2. Context

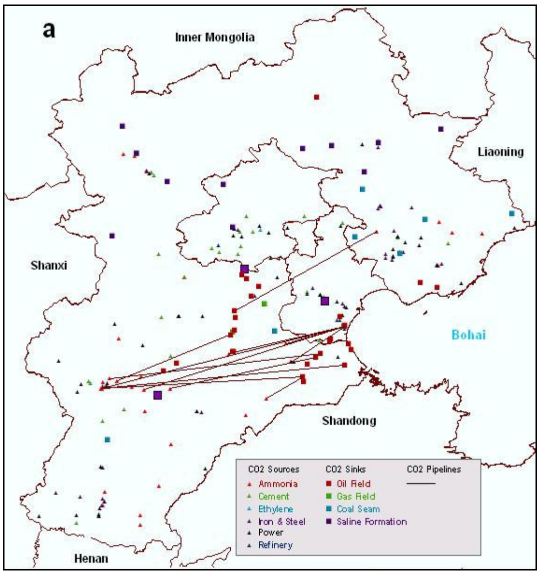
The Jing-Jin-Ji Region of North-Eastern China is a major contributor to China's CO_2 emissions profile. Two analyses have been performed (Chen, WP3 and Ma, WP4) that show the potential for this region to become a major CCS hub in the future.

A range of large-scale stationary point sources exist in this region, including 6 types of CO_2 sources. These sources combined contributed to an annual emission of 346.1 Mt CO_2 per year, of which 296 Mt CO_2 could be potentially captured and stored annually. A separate survey identified a range of large potential reservoirs in oil fields, gas fields, coal seams, and saline formations with a possible total storage capacity of 6791 Mt CO_2 based on published geological data.

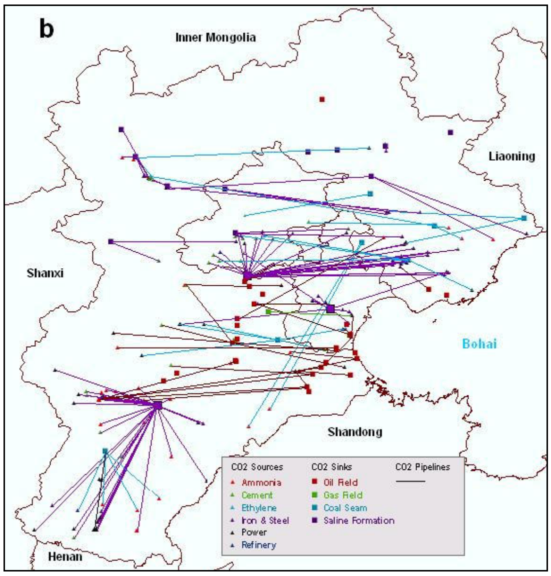


Distribution of CO_2 sources and sinks in Jing-Jin-Ji Region

Options for source-sink matching for two scenarios are shown below. Scenario A is the best economic performance case and scenario B is a maximum storage case. Scenario A contains completely the matching couples between ammonia plants and EOR fields, while scenario B requires matching all types of sources matching with all types of sinks.



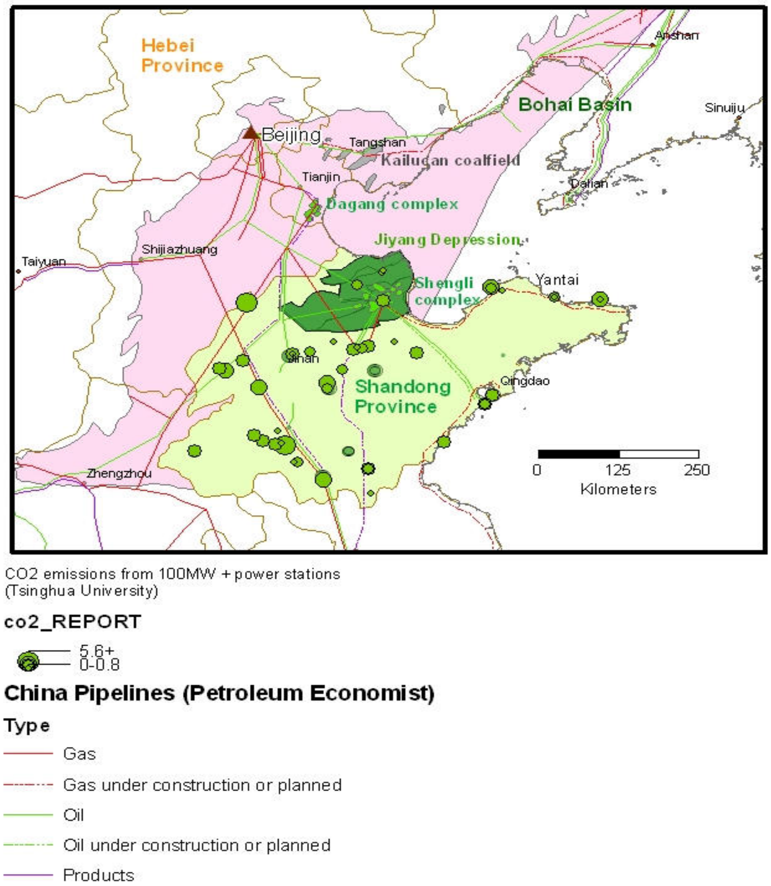
A. Best Economic Performance Case



B. Maximum Storage Case

5.3. Specific Scenarios

Two specific scenarios for a possible future demonstration of CCS have been used to focus this study. These are geographically focused upon the Bohai Basin region in the North East China.



Capture studies have been based upon a hypothetical polygeneration plant that is loosely modelled upon the Greengen IGCC plant being developed at Tianjin. Storage studies have considered at a high level four separate areas within the basin where storage might be possible. The scenarios may be summarised as follows :

Region	Bohai Basin region in the North East of China	
CO_2 source	3rd phase of GreenGen (Tianjin, 2012-2015)	
Transportation	Pipeline	
Feedstock	Shenhua coal, railway transport from Inner Mongolia	
Gasifier	TPRI / GreenGen	
Products	Power and methanol	
	Scenarios A (Small scale)	**Scenarios B (Full scale)**
CO_2 amount	0.1-1 million ton /yr	2-3 million ton /yr
CO_2 sink	EOR (Dagang or Shengli oilfield province)	Saline aquifer (Jiyang Depression or other)

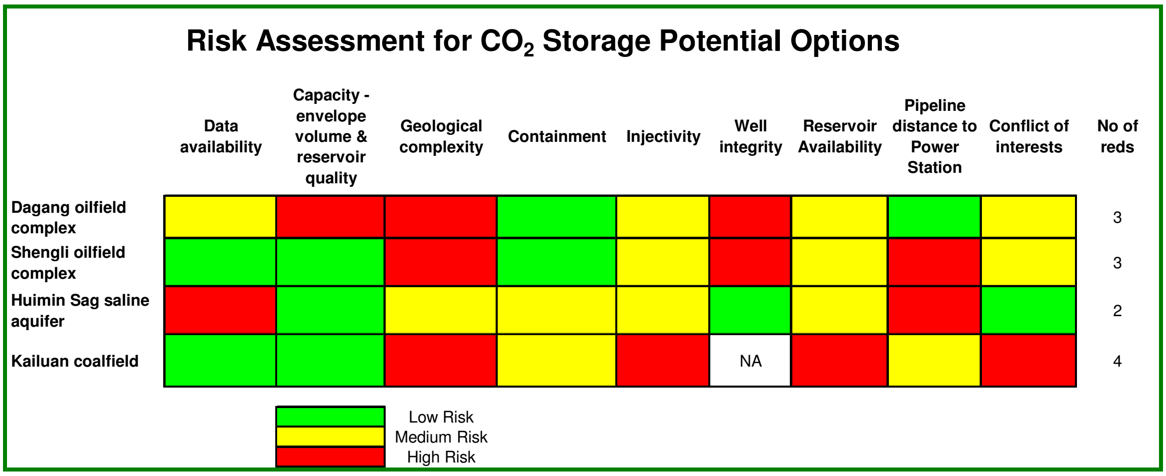
5.4. Storage options and risk analysis

The larger scale scenario flowrate of 2 – 3 million tonnes/year coupled with the economic modelling lifetime implies the need for 60 million tonne storage for a demonstration project. It would be prudent to increase the targeted capacity to 100 million tonnes to enable a higher flowrate in the later stages of the project and / or an extended lifetime.

Four geographic areas have been assessed at a high level to review their potential to contain a site that could be developed for CO_2 storage. It should be emphasised that the review performed to date is preliminary and does not in itself provide sufficient definition to enable the selection of a specific site.

The sites considered were :
- The Dagang oilfield province
- The Shengli oilfield province
- The Huimin sub-basin saline formations
- The Kailuan mining area

It must be stressed that the studies performed to date are scoping in nature and do not in themselves provide a sufficiently detailed assessment to enable any meaningful site selection at this stage.



5.4.1. Dagang Oil Field Complex

The Dagang oilfield province comprises 16 separate fields that have been developed using in excess of 700 wells. Despite this, relatively little data on these fields is available in the public domain.

The storage capacity of the Dagang oilfield province is small. The overall storage potential of the seven selected fields in the Dagang oilfield province was estimated at about 22 Mt, of these fields, the Gangdong oilfield had the largest capacity of 10 Mt CO_2. This would appear to limit the usefulness of the Dagang oilfield province to pilot scale activities. However, there is an alternative option - if the geology in the Gangdong Oilfield was sufficiently similar to that of the saline formations in the Huimin sub-basin then it might be possible to use Gangdong as a lower cost and lower risk option to build up some data on injectivity and compartmentalisation. To date, insufficient work has been done to assess whether the geology at Gangdong is a sufficiently good analogue for the Huimin sub-basin area.

Geologically, the Dagang oilfields are complex with sediments being deposited in fluvial environments with lateral and vertical variations in lithology. Structurally, multiple phases of faulting, uplift and erosion have also complicated the reservoirs. The clays of the Quaternary and the mudstones of the Minghuazhen Formation appear to act as effective cap rocks.

Injectivity is likely to be reasonable in the Gangdong Oilfield as the average permeability is described as 975 mD. Other fields in the Dagang oilfield province have permeabilities as low as 18 mD. However, the large number of wells that have been drilled for the production of oil gives rise to a concern that compartmentalisation may be an issue with a consequent risk that a large number of injection wells would be required.

With more than 700 wells in the Gangdong Oilfield, many of which are up to 40 years old, well integrity must be a significant issue.

As the field is in the declining phase of production the potential exists to undertake pilot CO_2 floods. Approximately 84% of reserves have been recovered. As the field production is in decline the potential for a conflict of interest between a pilot CO_2 flood and other field operations is probably not high.

5.4.2. Shengli oilfield province

The Shengli oilfield province has an extensive well and seismic dataset; 2400 exploration wells plus many more development wells. Substantially more of this dataset is available in the public literature. However, some data access issues remain, for example, only remaining reserves up to the year 2000 are available and more detailed information e.g. detailed depth and isopach contours for the reservoir horizons are not available publicly.

The Shengli oilfield province has a storage capacity for CO_2 in excess of that required for a 2 million tonne/year project for twenty years - the storage potential of selected fields in the oil province was estimated to be 463 Mt to 472 Mt depending on the remaining oil reserves in the oilfields (the most recent publicly available data are from 2000). The Shengtuo Oilfield was calculated to have the greatest potential storage capacity; 117 Mt to 186 Mt.

The reservoirs of the Shengli oilfields are compartmentalized and complex. There are nine oil-bearing horizons that contain many sand bodies, often with limited reservoir connectivity. In addition there are numerous phases of tectonic movements giving structural complexity which increases the overall geological complexity. This complexity requires a high number of production wells. In the Jiyang Depression, mudstones in the upper section of the Guantao Formation to the lower section of the Minghuazhen Formation form the main cap rock.

The porosity and permeability may be good with the potential for good injectivity. The Gudong Oilfield has porosity of 28 – 35% and permeability of 510 – 3118 mD in the Guantao Formation. However the fields are divided into many reservoirs which have poor communication with a likely need for many injection wells over time.

With the large number of wells in the Shengli oilfield province, many of which are up to 40 years old, well integrity must be a significant issue.

As the field is in the declining phase of production the potential must exist to undertake pilot CO_2 floods and the potential for a conflict of interest between a pilot CO_2 flood and other field operations is probably not high.

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5.4.3. Huimin sub-basin Saline Formations

As only four oil fields have been discovered in the Huimin sub-basin much less data are available than in the oilfields of the Shengli or Dagang oilfield provinces. As a consequence, there is more uncertainty in estimation of aquifer storage potential as a result of limited data availability resulting from the general lack of commercial interest in deep saline aquifers.

The storage capacity in the Huimin sub-basin has the potential to be large with an upper bound estimate of 22 Gt. This upper bound estimate will inevitably shrink significantly as further research identifies specific closed structures as targets for storage. However, it does suggest that the Huimin sub-basin saline formations might provide the basis for a regional CO_2 storage site. In saying this, it must be acknowledged that the limited geological data available leads to considerable uncertainty

The Huimin sub-basin is not a prospective region for hydrocarbons, as it appears that the formations which source some of the nearby Shengli oilfields are immature here. Seal properties of the Minghuazhen Formation mudstones and mudstones within the Guantao are expected to be good as these are the same formations which effectively seal the oil and gas reservoirs in the Shengli oilfield province. However, the lack of trapped hydrocarbons means that any regions being considered would need further investigation.

Limited data are available on the injectivity of the aquifer. The Linfanjia and Shanghe oilfields in the Huimin sub-basin have average porosities of 31% and 19 % respectively and measured permeabilities of 390 mD and 11 – 150 mD. However, there are large areas of the formations being considered for which there are few geological data. Data from the Shengli oilfield province implies that the aquifers are likely to be faulted and compartmentalised with a consequent risk that large numbers of injection wells be needed over time.

Well integrity is likely to be less of an issue as there are relatively few wells in the Huimin sub-basin

The saline formations do not appear to be used for other purposes so should be available for CO_2 storage. The potential for a conflict of interest between a pilot CO_2 flood and any oilfield operations is probably low.

5.4.4. Kailuan Mining Area

Substantial data exists on the 15 to 20 coal beds within the coal-bearing area of the Kailuan mining area (comprising the Kaiping and Jiyu coalfields) which covers 670 km^2.

The theoretical amount of CO_2 which could be adsorbed on the coals in the Kailuan mining area quoted in WP3 is very large (504 Gt). However, this relies on the CO_2 being able to access the coal. There is considerable uncertainty over the amount of this theoretical capacity that could actually be made available for CO_2 storage to avoid the risk of leakage or contamination of future energy resources.

The various limitations imposed on the coal beds in Kailuan mining area that would be available for CO_2 storage indicate that, generally, only thin coals in a relatively narrow depth window should be considered for CO_2 storage. It is probable that these thin coals will have substantial geological complexity. The coals are capped by overlying mudstones with good sealing ability. However, there are major faults in the Kailuan mining area and the sealing ability of these is not known. Although there is no noted leakage of CBM to the surface, this is a seismically active area, so consideration would have to be given to the potential for these faults to compromise the seals to permit free CO_2 a migration pathway into the overlying strata and to the surface.

Data (where available), indicate that the coals have low permeability (less than 3.6 mD) and porosity (average 3.5%), indicating that the injectivity will be low. Coal permeability varies widely and generally decreases with increasing depth as a result of cleat closure with increasing effective stress. Coalbed methane cannot be produced if permeability is less than 1mD (Zuber et al., 1996) and this is generally reached in the depth range of 1300–1500 m, which is considered also as the depth limit of possible CO_2 storage in coals.

In the Kailuan mining area, well integrity is less of an issue than it would be in oil or gas fields. However, boreholes are present in the mining area and so should be considered if CO_2 is injected to ensure they do not provide migration pathways to the surface for any free CO_2 not adsorbed onto the coal.

The various limitations imposed on the coal beds in Kailuan mining area that would be available for CO_2 storage indicate that, generally, only thin coals in a relatively narrow depth window should be considered for CO_2 storage.

5.5. Financing a CCS Demonstration Project : Understanding Costs

The contribution of this study to discussions on the financing of demonstration projects is to better assess the order of magnitude of costs that are likely to be incurred. The components of this are as follows:

5.5.1. Capture

The WP2 studies on cost benchmarking considered the differences between a reference case (IGCC without CCS) and a basecase (IGCC with CCS). For this study, a single product, electricity, was considered. CO_2 conditioning and compression are included within the cost of capture.

A financial analysis of the two cases (assuming 7000 operating hours per year) yielded the following :

Item	*Unit*	*Reference case (without CCS)*	*Base case (with CCS)*	*Increasing*
COE (gross)	¥/kWh	0.345	0.444	29%
COE (net)	¥/kWh	0.400	0.578	44%
CO_2 emission(net)	kg CO_2/kWh	0.792	0.094	-88%
CO_2 captured (net)	kg CO_2/kWh		0.991	
investment	G RMB	3.31	4.13	25%
Levelized investment (gross)	¥/kW	11681	17789	52%
IRR		0.09%	-12.41%	
NPV	G RMB	-0.75	-2.99	

Based upon the definitions in the IPCC special report on CCS, the *cost of CO_2 captured* and the *cost of CO_2 avoided* would be :

- **Cost of CO_2 avoided :**

Cost $_{avoided}$ = [COE $_{base}$ – COE $_{ref}$]/[$CO_{2\ ref}$ – $CO_{2\ base}$]=(0.578-0.400)/(0.792-0.094)*1000

= 225 RMB/ t or **22.50 €/t** (assuming €1 = 10 RMB)

- **Cost of CO_2 captured :**

Cost $_{Captured}$ = [COE $_{base}$ – COE $_{ref}$] / $CO_{2\ captured}$ =(0.578-0.400)/0.991*1000

= 179 RMB/ t or **17..9 €/t** (assuming €1 = 10 RMB)

5.5.2. Transport

The following assumptions (based upon studies in WP2 and WP3) have been used to estimate transport costs :

- CO_2 flowrate: 3 million tonnes/year
- Pipeline diameter: 300 mm (12 inches)

- Facility lifetime: 20 years
- CO_2 inventory: 60 million tonnes
- Pipeline Capex: €21,500 / in-mile (average of data from WP2 and WP3)
- Pipeline Opex : €3450/mile/year

This yields a unit cost for a 100 mile pipeline of:

Unit Cost = Capex / CO_2 inventory + Opex / Annual throughput
= (€21500 / in-mile * 12 in *100 miles) / 60,000,000 tonnes + (€3450/mile-year*100 miles)/3,000,000 tonnes/year
= €0.43 / tonne / 100 miles + €0.12 / tonne per 100 miles

= **€0.55 / tonne per 100 miles**

5.5.3. Storage

Storage costs are assumed to arise from the following components :

- **Appraisal costs:** it is assumed that producing oilfields (Dagang oilfield province and Shengli oilfield province) will require no new appraisal. However, the Huimin sub-basin and possibly Kailuan mining area are assumed to require a full appraisal sequence to identify and evaluate suitable storage locations. Cost assumptions are as follows :
    - 2500 km 2D seismic €5 million
    - 500 km^2 3D seismic €15 million
    - 10 appraisal wells €30 million

This yields a unit cost **calculated for a 60 million tonne storage site** of :

Unit cost = €50 million / 60 million tonnes
= **€0.83 / tonne**

- **Wells:** it is assumed that new wells will be required as CO_2 injectors and that any existing production wells will require remediation or upgrading for high pressure CO_2 service. Cost assumptions are as follows :
    - High spec. injection well €5 million
    - Integrity screening : €0.1 million / well
    - Remediation & upgrading : €2 million / well

Although for the most part, the potential storage formations have a moderate to high permeability, the degree of compartmentalisation is a concern with the result that the number of wells required is a major uncertainty. Costs have been estimated for a range of 8 – 15 – 30 wells (20 – 10 – 5 million scf/day/well for 3 million tonnes/year)

It is assumed that remediation and upgrading may be required for wells in the producing oilfields (Dagang and Shengli) but is not required for the saline formations options (Huimin sub-basin) or coalfield options (Kailuan). It is arbitrarily assumed that 300 wells may need to be screened for integrity for high pressure CO_2 and that remediation and/or upgrading may be required on up to 50 of these.

This yields a unit cost for a 60 million tonne storage site of:

Without remediation of the existing wells

Unit cost = €40 – 75 - 150 million / 60 million tonnes
= **€0.67 – 1.25 – 2.50 / tonne**

With remediation of the existing wells

Unit cost = €40 – 75 - 150 million / 60 million tonnes + €130 million / 60 million tonnes
€2.84 – 3.42 – 4.67 / tonne

- **Monitoring :** for the purposes of this study it is assumed that a demonstration of geological storage of CO_2 would be accompanied by an extensive monitoring campaign. There are many options for a monitoring campaign and it is premature to focus on individual techniques before key uncertainties have been established for the demonstration site. Accordingly, it is assumed that the monitoring over the facility life can be divided into an initial intensive five year period and then a much reduced level of monitoring for the remainder of the project. Cost assumptions are as follows :
    - Initial five years €40 million (based on range of major CCS projects)
    - Remaining 15 years €10 million

This yields a unit cost for a 60 million tonne storage site of :

Unit cost = €50 million / 60 million tonnes
€0.83 / tonne

5.5.4. Integrated Cost

All cases considered lie in the range €26 – 30 / tonne of CO_2 avoided, this cost being dominated by the cost of CO_2 capture, conditioning and compression (80 – 88% of total).

	Distance	Capture	Transport	Site Appraisal	Wells	Monitoring	**Total**
	km	€/t (*)	€/t (*)	€/t (*)	€/t (*)	€/t (*)	€/t (*)
Dagang oil province	70	22.50	0.24	0	2.84–3.42–4.67	0.83	**26.41 - 26.99 - 28.24**
Gudao oilfield	200	22.50	0.68	0	2.84–3.42–4.67	0.83	**26.83 - 27.41 – 28.66**
Huimin sub-basin	250	22.50	0.85	0.83	0.67–1.25–2.50	0.83	**25.68 - 26.26 – 27.51**
Kailuan mining area	170	22.50	0.58	0.83	0.67–1.25–2.50	0.83	**25.41 - 25.99 - 27.24**

(*) assuming an exchange rate: 1€ = 10 RMB

It should be stressed that these costs have a considerable uncertainty associated with them and should be treated as indicative only.

5.6. Policy and regulation

Policy and regulatory issues relevant to CCS inside and outside China are summarised under the following three topics.

5.6.1. Issues for Regulators to Consider

The following guidance for regulators on issues to be considered when developing regulatory frameworks for CCS was developed by the CO_2 Capture Project (CCP, www.co2captureproject.org)

Building a framework to regulate CCS

Widespread deployment of CO_2 Capture and Storage (CCS) will require standards and criteria to provide assurance of the long-term security of CO_2 Geological Storage (CGS).
— CO_2 Capture Project, *Policy Principles Paper: A Framework for Certification and Operation of CO_2 Geological Storage Sites*

1 Site certification
2 Operation
3 Closure
4 Post closure

▲ An operational framework

Site certification

Necessary preliminary steps before initial site certification:

1 Local and national authorities must grant the right to store CO_2.
2 The government and the operating company will need to agree to both the initial site conditions and the operational limits of the site.
3 The capacity of the site must be determined.
4 The quality of the site must be assessed. The risk of leakage will need to be evaluated.
5 A risk assessment should address factors, such as the strength of the seal and the pressure and chemistry of fluids and gases within the reservoir.

A high-quality storage site should fit the following criteria:

- The site must be of sufficient depth not to endanger underground sources of drinking water. The ideal depth would be between one and three thousand metres.
- The formation should contain a large amount of potential storage space.
- The site should have an effective trapping mechanism with thick, impermeable confining rock layers (such as shales) that are free of major (non-sealing) faults.

Operation

The length of time it takes to inject the CO_2 into the site could vary from a few years to decades.

Meter → Regulate → Examine → Comply → Adhere → Report

▲ Operational tasks

Site operators should undertake the following operational tasks:

- Meter the pressure and regulate the flow-rate.
- Examine the composition of the CO_2 stream to detect impurities. CO_2 from industrial sources could be mixed with other gases and trace elements, which may need to be removed before the CO_2 is stored.
- Comply with local regulations on the use of CO_2-resistant construction materials in wells, cement plugs and surface facilities.
- Adhere to a monitoring regime that will include updates to, and validation of, the reservoir modelling.
- Report performance results to a government regulator. (The regulator may intervene if performance measurements differ markedly from the modelling predictions).

Closure

- Commercial businesses may not exist for very long, so to ensure public acceptance of geological storage, it is important that long-term stewardship of storage sites remain with nations or states.
- When the injection of CO_2 has ended, the operator should apply to the regulator for a closure certificate.
- After certification has been agreed, the operator can remove the equipment and buildings above the site, unless long-term monitoring is required.
- Site stewardship should revert to the appropriate government authority.

Post-Closure

- Post-closure requirements will differ from one site to the next because some sites will present no risk and others may require long-term monitoring.
- A well-chosen site, which has performed as expected and required, may not need long-term monitoring.
- A poorly performing site may need continued monitoring and possibly remediation or mitigation.

5.6.2. Initiatives Outside China

Over the last five years there have been activities in a number of countries to consider the regulatory requirements of CCS (and in particular, CO_2 storage). Some of these jurisdictions are now in the process of introducing regulatory frameworks specific to CCS. The following table is a summary of the status of these activities in Q1 2009.

	EU		USA		Canada		UAE		Australia	
	EOR+	Storage	EOR+	Storage	EOR+	Storage	EOR+	Storage	EOR+	Storage
Access to Pore-space	MS Pet	No	Landowner	Landowner	Province	Acid Gas	Pet	No	Pet	Comm Licensing
Permission to Inject	MS Pet	CCS Dir	EPA/OGCC	EPA Rule	O&G	Acid Gas	Pet	No	Pet	FDP
Storage Security (financing)	No	CCS Dir	No	No	No	Acid Gas	No	No	No	FDP
Legal Project Closure	MS Pet	CCS Dir	EPA/OGCC	EPA Rule	O&G	Acid Gas	Pet	No	Pet	Site Closure Cert.
Long-term Responsibility	MS Pet	CCS Dir	Landowner	Landowner	Province	Acid Gas	Pet	No	Pet	Feds

5.6.3. Initiatives Within China

Tsinghua University – WRI Initiative

Tsinghua University is partnering with WRI to develop guidelines for China's deployment of CCS technology. Tsinghua University has assembled a steering committee that includes China's leading CCS experts. This team met for the first time at Tsinghua in December 2008 and began what will be a two-year effort. This project is being funded with support from the U.S. Department of State under the Asia Pacific Partnership

The project is modelled on a successful effort that WRI helped implement in the U.S., in which a diverse set of stakeholders developed a comprehensive set of guidelines for CCS projects. A Chinese version of the guidelines would foster better understanding in China of how to develop responsible CCS projects, and would provide information to guide decision-making as China addresses the climate-coal challenge.

Further information was presented at the STRA-CO2 meeting in Beijing in May 2009: http://www.euchina-ccs.org/media/docs/Beijing%20workshop/Deborah%20Seligsohn%20(EN).pdf

STRACO2

The EU project **STRACO2** concluded in 2009. It was designed to support the ongoing development and implementation of a comprehensive regulatory framework in the EU for Carbon Capture and Storage (CCS) technologies for zero emissions applications but also aimed to assist in supporting and building a basis for EU-China cooperation on CCS.

STRACO2 had five major objectives: (1) Incentivisation schemes; (2) Financing mechanisms; (3) International trade (and dialogue with associated international bodies); (4) Technology transfer; (5) Socio-economic impacts

Further information on STRA-CO2 is available at : http://www.euchina-ccs.org/objectives.php

5.7. Conclusions and Recommendations for Future Work

5.7.1. Conclusions

1. The Jin-Jing-Ji region of North-East China is a material contributor to China's overall GHG emissions profile. However, analyses indicate that this region has the technical potential for CCS to make a significant contribution to reducing emissions in the event that global dialogues continue to show that this is necessary.
2. Two scenarios have been used to focus this study to screen options for a possible CCS demonstration project. These have considered capture of CO_2 from the gasification of coal and storage in one or more geological formations in the Bohai Bay geological basin.
3. Storage for the smaller scale scenario (0.1 – 1 million tonnes/year) could be accommodated in the Dagang or Shengli oilfields. Storage for the larger scale scenario (2 – 3 million tonnes/year) could be accommodated in the Shengli oilfield province (in a number of fields) or potentially in the saline formations in the Huimin sub-basin area.
4. The assessment of geological storage options performed to date is at a scoping level only. Large uncertainties remain that will require a sustained geological appraisal effort to address. Specific issues include :
   - Only public domain data has been used limiting the available database
   - Very limited data are available to describe the saline formations of the Huimin sub-basin.
   - As a consequence, estimate of storage capacity have been made using analytic approaches rather than based upon geological and dynamic modelling
   - Well numbers for CO_2 injection are a major uncertainty given the potential for compartmentalisation of the storage formations. Estimates for the number of wells required could easily be in error by a factor of two.
   - When considering storage options in existing oilfields, the large number of wells gives rise to concerns over well integrity. This has not been fully reviewed in the current study.
5. Costs for CCS for the larger scale scenario have been estimated as :
   - Capture, conditioning and compression : €22.50 / tonne CO_2 avoided
   - Transport, storage and monitoring : €3 – 6 / tonne CO_2 stored (depending on the number of injection wells required)

This yields an integrated cost for CCS for the larger scale scenario of :

CCS cost = approx. €25 - €30/ tonne CO_2 avoided (253 – 284 RMB / tonne CO_2 avoided)

6. In common with most other countries, China does not yet have a functioning regulatory framework for CCS and in particular the geological storage of CO_2. Substantial progress has been made in the last two years in clarifying the issues for regulators to consider and in initiating activities that can lead to the formation of a regulatory framework.

5.7.2. Recommendations

1. The work on capture cost benchmarking should be extended to consider the impact of having both methanol and electricity as product streams.
2. A sustained campaign of geological assessment is required to progress from the current high-level scoping study to a point where selection of a storage site will be possible.
3. It is recommended that further storage site work should focus upon the Dagang oilfield province, the Shengli oilfield province and the saline formations of the Huimin sub-basin. Further work on the Kailuan mining area should wait until there is a further assessment of the implications of CO_2 storage on the economic value of the coal.
4. Dagang is the closest potential storage site to the Tianjin site but also the smallest. A pilot test of EOR is an option but could not be scaled up further. However, consideration should be given to

whether the geology in the Dagang oilfield province is sufficiently similar to that in the Huimin sub-basin to enable early data to be gathered on injectivity and compartmentalisation.

5. A basin charge study would be useful to consider why the distribution of hydrocarbons is as it is. This could increase confidence in the sealing capacity of potential caprocks in the Huimin sub-basin area.
6. Detailed geological models are required to enable further assessment of the storage sites. This will require access to existing original data or acquisition of new data.
7. Dynamic modelling of CO_2 injection should be performed using development scenarios to enable estimates of storage capacity to be refined.
8. A combination of analogue data and modelling studies should be used to better constrain the projected injection well count.
9. Well integrity studies are required to better understand the leakage risk posed by existing wellbores in producing oilfields
10. In future work attention should be given to identifying and avoiding potential conflicts of interest.

6. Conclusions

The main conclusions drawn during the COACH project are summarized here below:

- **Knowledge sharing and Capacity building**
  - An important activity was deployed to perform an efficient knowledge sharing within the project. As such several workshops were organised both in China and in Europe involving COACH partners only or in conjunction with companion projects such as UK-NZEC, StraCO2, GeoCapacity.
  - Two websites were created, one to exchange information between COACH partners and one open to the public www.co2-coach.com.
  - A survey of CCS activities in both China and Europe was carried out and updated during the project.
  - To promote the work performed within the project, 9 presentations at international conferences, 5 papers were accepted for publication in international journals, 3 books were edited referring to the COACH project, 1 presentation of the COACH project was published in the European Parliament Magazine and several interventions in radio broadcasts were organised.
  - Regarding capacity building, in addition to the training sessions and workshops organised, two one-week long Schools were set up, one in April 2009 in Hangzhou and the other in October 2009 in Beijing. These two Schools attracted in total 80 Chinese students and 30 European students.
- **Capture technologies**
  - A generic IGCC concept implemented with CO_2 capture has been defined and compared against a plain IGCC based on the GreenGen Phase I system without CO_2 capture.
  - Benchmarking was made between a reference case for which a gas turbine burns a low-calorific syngas and a base case consisting of a turbine burning an hydrogen enriched gas mixture diluted with nitrogen. Provision for methanol production was made as well but was not reviewed in details.
  - The CO_2 capture cost was found to amount to €18/tCO_2 whereas the **cost of the CO_2 avoided** was a little bit higher amounting to **€22/tCO_2**.
  - CO_2 handling was also addressed for transporting and storing the CO_2 safely. Three cases were studied for transporting the CO_2 from the Tianjin power plant to the Shengli oilfield province by rail, pipeline and ship
- **Storage capacity assessment**
  - Potential CO_2 storage sites have been investigated in the part of the Bohai Basin located in the Shandong Province, East China. Selected oilfields, saline aquifers and unmineable coal beds were considered. Possible test sites are available in some of the oil fields.
  - The coals of Kailuan mining area have a high ability to adsorb CO_2, but the CO_2 injection rate is anticipated to be low. Enhanced coalbed methane recovery could be considered.
  - The aquifers show a large storage potential, but further geological investigation is required.
  - Some of the oilfields may be suitable for an enhanced oil recovery pilot. Injecting CO_2 into an mature oil reservoir cannot only store CO_2, but also enhance the oil recovery.
  - The storage potential in oil fields is however much smaller (**10–500Mt**) than in the saline aquifers (**approx. 20Gt**).
- **Integration and recommendations**
  - Two scenarios have been designed to screen options for a possible CCS demonstration project. These have considered capture of CO2 from the Tianjin IGCC power plant and storage in one or more geological formations in the Bohai Bay geological basin.

- Storage for the smaller scale scenario (0.1 – 1 million tonnes/year) could be accommodated in the Dagang or Shengli oilfields. Storage for the larger scale scenario (2 – 3 million tonnes/year) could be accommodated in the Shengli oilfield province (in a number of fields) or potentially in the saline formations in the Huimin sub-basin area. For each of these options, a preliminary risk assessment was performed.
- **Furthermore, a thorough cost analysis was performed. This lead to an integrated CCS cost which was found to lie in the range €25-30/tCO_2.**
- To end with, policy and regulation issues were addressed.