Feasibility Study of CCS-Readiness in Guangdong (GDCCSR)

2010 Annual Report

The GDCCSR Team
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Feasibility Analysis of CCS-Readiness in Guangdong (GDCCSR)

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Project Duration
April 2010 to March 2013
Summary

The project “Feasibility Analysis of CCS-Readiness in Guangdong (GDCCSR)” was launched on March 18, 2010. The project duration is from April 2010 to March 2013. The project is aimed to investigate scientifically if CCS is needed and feasible in Guangdong, and to suggest roadmap and policies for its development.

In Nov.23, 2010, the first annual meeting of the GDCCSR project was held to examine the progress to date and to discuss future works. This report was produced based on the reports from sub-groups to the meeting.

Although the GDCCSR project has progressed only for 8 months, it has fulfilled most of the annual tasks, and even exceeded the expectation. Major outcomes of the project are as follows:

1) CO$_2$ emission

   Energy consumption: Guangdong is characterized by high energy consumption, and high dependency on import energy due to its low energy resources. In 2008, the total energy consumption was 230.7 million tce, and primary energy consumption was 176.8 million tons. The import energy shared 95% of the total energy consumption. The final energy consumption of Guangdong was dominated by electricity (47.9%), oil (21.6%), and coal (13.7%). Power + Oil + Coal reached 83.2%. These are the main carbon emission sources of Guangdong. From 1990 to 2008, Guangdong’s annual energy production increases in average 8%, while the annual consumption increases in average 10.16%

   CO$_2$ emission: Calculated from final energy consumption multiplied by their emission factors recommended by IPCC, the total CO$_2$ emissions of Guangdong in 2008 was about 0.53 billion tons. Among this the CO$_2$ emissions from power, industry, transportation, construction and agriculture sectors were 56%, 31%, 6%, 4%, and 3%, respectively. Of the electricity generated in Guangdong, 78% was from thermal power, most of them from coal-fired power.

   Major point sources of CO$_2$: There are 158 major emission sources (an annual emission more than 0.1 Mt CO$_2$), and their total annual emissions are up to 324.73 Mt. The power sector is the largest CO$_2$ emitter in Guangdong. The emission from thermal power plants accounts for 79% of the total emission. Major point sources (MPS) of CO$_2$ emission are mainly located in the pan-Pearl River Delta Region, especially in Dongguan, Guangzhou, and Shenzhen. Secondarily, the carbon emission sources in Jiangmen and Shantou are also high. The MPS of steel industry mainly reside in Shaoguan, Guangzhou, and Zhuhai; while those of petrochemical industry are mainly in Guangzhou, Maoming, and Huizhou.

2) CO$_2$ Storage

As in PACOS-GD project the inland basins are proved having low capacity, and the Pearl River Mouth Basin has been studied, during this period we concentrated to the study of the Beibuwan, Qiongdongnan, and Yinggehai basins offshore in the northern South China Sea.
**GIS and Storage Capacity:** Data have been collected from published sources and entered the database. GIS system has been in construction. Geological conditions related to CO₂ underground storage have been analyzed, including stratigraphy, structure, crustal stability, geothermal gradient, seal and aquifer distribution and properties, and favorable seal-aquifer assemblages. Detailed descriptions on the basins have been presented in the project report.

**Early opportunity for storage:** The LF2G1 structure in the Lufeng Sag, northern Pearl River Mouth Basin was selected. Relevant data from drillhole and 2D seismic survey were provided by CNOOC-Shenzhen.

Ongoing analysis has shown that LF2G1 has a good potential as a site for CO₂ storage. The structure is 210 km southeast off the most industrialized eastern Pearl River Delta. It is a structure dome with a total areal of 160 km² and water depth of 100 m. It has at least two layers of high quality sandstone aquifers with a total thickness of >200 m. The upper layer is capped with thick mudstone seals, but the caprock property for the lower layer needs further study.

A rough estimation on the storage capacity of LF2G1 is over 300 Mt CO₂. This may become a good CO₂ sink to match the major emission sources in the eastern Pearl River Delta.

3) **Cost Estimation**

Costs in CO₂ transportation (by pipeline) and injection have been analyzed based on data from foreign sources. Data from Chinese source need to be collected in the next year.

4) **CO₂ Capture Ready Promotion**

New power plants are our first choice for capture-ready promotion. Principles concerning the selection process have been established. 3 power plants (the CNOOC Huizhou refinery project phase II, the Shenzhen Energy Binhai power plant phase I, and the Sanshui Hengyi Power Plant) were contacted as our potential target.

A case study of Shenzhen city in Guangdong in southern China is presented, based on engineering and cost assessment studies and stakeholder consultations and building on existing geological surveys and infrastructure plans. The simulation results show that financing ‘CCS Ready’ at regional planning level rather than only at the design stage of the individual plant is preferred since it reduces the overall cost of building integrated CCS systems. Making new plants CCS ready or planning a CCS ready hub should consider existing large emissions sources is recommended.

5) **Energy-Carbon Control System Modeling**

The AIM-Technology Model jointly developed by National Institute for Environmental Studies (NIES) and ERI is selected as the platform to constitute CCS technology and economy assessment model for Guangdong.

Four scenarios are set to evaluate the development of CCS in Guangdong Province, i.e. baseline scenario, emission reduction scenario, policy scenario (including capture-ready policy), and high development of CCS scenario.

Adjustments were made on technology categories and relevant parameters in the model. Some types power technologies were subdivided, while other types were merged, CCS relevant technology categories were added, and the model parameters reflecting policy and measures on
CCS technology were added as necessary. Data collection has been in progress with the cooperation of other project partners. These including the data on energy consumption, power generation, and carbon emissions in Guangdong, the data on the efficiency of different power generation technologies, and the data on economic cost related to CCS.

6) Capacity Building & Public Awareness

**Network:** In order to build capacity and public awareness on CCS in Guangdong, we have established the first CCS partnership in China: the China Low-carbon Energy Action Network (CLEAN). CLEAN provides a communication and cooperation platform for promoting carbon capture and storage readiness in Guangdong and in China. So far 52 members from research institutions, industry (electricity, oil, clean energy), finance, NGO, and embassy/consulates jointed CLEAN.

**Website:** Two websites were created: the GDCCSR project website (www.gdccs.org) and the CLEAN website (www.clean.org.cn).

**Workshops:** Three meetings/workshops have been held by the project: the GDCCSR Launch Meeting in March, the CCS seminar-Summer Assemble in June, and the CLEAN network launch meeting in August. High rank officials from UK, China, and Guangdong attended the meetings. High level presentations, including those given by Chinese academicians, leading enterprises, and UK experts, have been made in each of the meetings.

**Links with government and industry:** These have lead to the following results:

Guangdong government has begun to accept the concept of CCS. In the “Action Plan for the Low-carbon Pilot Province of Guangdong” drafted in Oct. 2010, CCS has been included for the first time as a low-carbon technology to be developed. This is a major progress compared with the fact that 8 month ago there was no consideration on CCS at all in drafting the provincial low-carbon roadmap.

CNOOC-Shenzhen agreed to support out study of offshore CO₂ storage. This made possible for the LF2G1 structure as the target for early opportunity of offshore CO₂ storage.

CNOOC Huizhou refinery project phase II became interested in CCS deployment. Relevant proposal was written jointed by the Huizhou phase II and the GDCCSR team, and was sent to the CNOOC headquarter by the Huizhou group and to the UK prime minister by the British Consulate General in Guangzhou. This may be the first step towards a proposal for a demonstration project composed of the CO₂ sequestration from the Huizhou phase II, a pipeline transportation, and an offshore CO₂ storage in the LF2G1 structure in the Pearl River Mouth Basin.

7) Future plan

The progress in the first 8 month of the GDCCSR project has set a solid background for proceeding to the next two years. Major tasks for the next two years are outlined in the project roadmap and briefed in the Chapter 7 of this report. In short, in the next year we will complete the majority of the research work of the project, and in the third year all the research tasks including the system modeling will be completed, and the CCS roadmap and policy recommendations will be draw. We are confident that with the firm support of BCG and GCCSI and through the hard and efficient works of the team members, the GDCCSR project will be a good success as a key to open the CCS door in Guangdong.
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Preface: Project outline and 2010 Tasks

1 Project outline

The project “Feasibility Analysis of CCS-Readiness in Guangdong (GDCCSR)” was launched in Guangzhou, China on March 18, 2010. The project was funded with 4.5 million RMB from the Strategic Programme Fund (SPF) for Low Carbon and High Growth of the UK Foreign and Commonwealth Office and from the Global CCS Institute (GCCSI) in Australia. The project duration is from April 2010 to March 2013. The project implementers are groups from the following institutions:

- The South China Sea Institute of Oceanology, CAS (SCSIO), lead by Di Zhou;
- The Guangzhou Institute of Energy Conversion, CAS (GIEC), lead by Daiqing Zhao;
- The Wuhan Institute of Rock and Soil Mechanics, CAS (IRSM), lead by Xiaochun Li;
- The Energy Research Institute (ERI) of the China NDRC, lead by Qiang Liu;
- The Linkschina Investment Advisory Ltd. (LC), lead by Jia Li;
- The Edinburgh University (ED), lead by Jon Gibbins;
- The Cambridge University (CAM), lead by David Reiner.

Guangdong Province in southern China is China’s largest provincial economy, with an economy larger and more diverse than that of Saudi Arabia. In 2008 its GDP reached ~€357 billion with roughly 50% of this coming from industry. Guangdong’s legacy within China is one of leading reform – with the Special Economic Zones of the 1980s pioneering the development of China’s economy. The current provincial government is actively promoting the low-carbon economic development.

However, CCS was not featured in the Guangdong’s conceptual model for low carbon economy by the time the GDCCSR project was launched. Major reason was the knowledge gap: To that date all of the major CCS projects in China have focused on the regions north of the Yangtze River, with no substantial research having taken place in China’s wealthy manufacturing provinces of the south. Although Guangdong’s electricity industry has been highly involved in the recent wave of promoting new IGCC plant with three under consideration for Guangdong, including two of 1200 MW, to that date there has been no consideration on how to deal with the CO₂ captured in these plants.

The GDCCSR project is the first CCS-related project in Guangdong and in southern China. The aim of the project is to demonstrate scientifically if CCS is needed and feasible in Guangdong, and to suggest roadmap and policies for its development. A flow chart of the project is presented at the end of this preface.

2 Project roadmap and 2010 tasks

According to the project roadmap, the tasks in 2010 from April to Dec. are as follows:

1) The emission of major industrial point sources in Guangdong
a) CO₂ point sources in Guangdong, including CO₂ total emission & variation, and carbon emission in different industries;
b) Database creation, including Major point source (MPS) emission and distribution;
c) Point source emissions calculation;
d) Analysis of energy production/consumption/trade;
e) Research on 5-8 major emissions sources;

2) The storage capacity onshore and offshore Guangdong
   a) Data collection and compilation;
   b) GIS of oil & gas fields (to be continued);
   c) GIS of saline formations (to be continued);
   d) Geological analysis and mapping;
   e) Early opportunity for storage.

3) The cost and benefit of implementing CCS in Guangdong;
   a) Cost of CO₂ capture (to be continued);
   b) Cost of CO₂ transportation (to be continued);
   c) Cost of CO₂ injection (to be continued).

4) The benefit of capture ready and case studies;
   a) Identify sites for CCS retrofitting (to be continued);
   b) System modeling and feasibility study of CCR power plant (to be continued).

5) The contribution of CCS to the low carbon economy and its roadmap up to 2050;
   a) Building GD CCS model, including:
      i. Data collection and analysis
      ii. Future scenario design
      iii. Economic model and its parameters
      iv. Technical model and its parameters

6) Capacity building and public awareness.
   a) Regional CCS network;
   b) GDCCSR website;
   c) International workshops;
   d) Meeting with government and stakeholders.

These tasks have been fulfilled as panned by now. This report summarizes major outcomes based on the reports of sub-groups. Among these, Chapter 1 reports the progress made by the GIEC group; Chapter 2 by the SCSIO group, Chapter 4 by the IRSM group, Chapter 5 by the LC, ED, and CAM groups, Chapter 6 by the ERI group, and Chapter 7 by mainly the LC group, but added with works of other groups. The project leader Di Zhou compiled the report.

The project team thanks the funding from the UK government and GCCSI, thanks BCG and especially Wayne Ives for your excellent management, and thanks Bill Senior and Andrew Minchener for advices, and thanks the institutions for hosting the project team works.
Chapter 1

CO₂ Emissions in Guangdong

1.1 Energy supply and consumption

1.1.1 General status

Guangdong has been one of the leading economies in China. Especially her Pearl River Delta has been producing nearly 10% GDP with only 3.6% national population in 0.25% land area. In recent years, the energy efficiency has been improved in Guangdong. In 2008 the energy consumption in unit GDP was 715 tone standard coal per 1 million RMB, decreased by 10 % compared with that in 2005, but still much higher than that in developed countries.

Since the opening up Guangdong’s energy demand was soaring with the rapid economic growth. The total energy consumption reaches 230.7 million tce (Fig.1-1-1) which is 8.1% of the total national consumption. It increased 5.29% compared to 2007. Coal, oil and power occupy 13.7%, 21.6%, and 47.9% of the end energy consumption respectively.

Guangdong has low energy resources of ≤ 30 tce per capita, which is only 1/20 of the national average. Thus its own energy production is much lower than the energy import. For example, in 2008 the provincial energy production was 44.1 million tons, import energy from other provinces was 168.9 million tons, and from other countries 51.1 million tons. Its own energy production occupies only 19.13% of the energy consumption (Fig. 1-1-1). From 1990 to 2008, Guangdong’s annual energy production increases in average 8% (Fig. 1-1-2), while the annual consumption increases in average 10.16 % (Fig. 1-1-1).
For years Guangdong was facing great challenge in lacking of domestic energy supply and great dependency on import. The fast development of automobile industry, co-operation with Hongkong and Macau, and the role of the World’s manufacturing centre all require sustainable energy supply. Therefore the energy demand of Guangdong will not decrease, and the pressure will grow in the foreseeing years.

1.1.2 Energy Structure

In 2008, Guangdong’s energy production share was 44.5%, 37.4%, and 18.1% of the total from crude oil, power, and natural gas, respectively (Fig. 1-1-3).

In 2008, Guangdong’s primary energy consumption was 176.8 million tons, of which the share of coal is 50.8%, of power 20.5%, of crude oil 24.6%, and of gas 4.1% (Fig. 1-1-4).
In 2008, Guangdong’s final energy consumption was 222.8 million tons, of which power occupies 47.9%, oil 21.6%, and coal 13.7%. Power + Oil + Coal reach 83.2%. These are the main carbon emission sources of Guangdong (Fig. 1-1-1-5).

![Figure 1-1-5 Guangdong’s final energy consumption mix](image)

1.1.3 Energy Import Dependency

In 2008, Guangdong expanded collaboration with other provinces and increased energy import to 220 million tons, which shares 95% of the total energy consumption. This import includes 168.9 million tce import from other provinces and 51.1 millions tce import from other countries. Import from other provinces dominates the total import amount with a share of 76.77%. Import from abroad remains 23.23% (Fig. 1-1-1-6).

![Figure 1-1-6 Guangdong energy supply import dependency](image)

According to the type of energy, the import energies are mainly raw coal, electricity, crude oil and fuel oil. In 2008, 100% of raw coal, 20.9% of electricity, 52.6% of crude oil and 89.5% of fuel oil need to be imported into Guangdong, occupied 77.6% of the total energy import. Raw coal is transferred from the northern coal-producing provinces and electricity is from the west. In 2008, the amount of raw coal transferred from other provinces is 67.55 million tce and electricity is about 20.1million tce.

The proportion of primary energy production accounts for the total energy consumption is decreasing since 2000. Energy consumption excessively depends on the import, which has
gradually become a key factor to restrict the development of Guangdong.

### 1.2 Total CO$_2$ Emission

#### 1.2.1 Methodology of CO$_2$ Emissions Calculation

CO$_2$ emissions that cause climate change are mainly generated from large-scale utilisation of fossil fuel. In this section, the current status of the composition and total amount of CO$_2$ emissions in Guangdong province are analysed. CO$_2$ emissions are calculated from its final energy consumption multiplied by their emission factors which are recommended by IPCC. Data used is from the “Statistical Yearbook of Guangdong Province in 2009”.

In this calculation the CO$_2$ emissions from renewable and nuclear energies are assumed to be zero. The China Southern Power Grid baseline emission factors are used as the emission factors of electricity sent from outside region into Guangdong (that is, “purchased electricity”). The total emissions of Guangdong province and its various sectors are calculated as follows:

- **Total CO$_2$ emissions of Guangdong Province**
  \[ \text{Total CO}_2 \text{ emissions of Guangdong Province} = \sum (\text{Species i energy consumption} \times \text{emission factor}) \]  

- **Total CO$_2$ emissions of Power Sector**
  \[ \text{Total CO}_2 \text{ emissions of Power Sector} = \sum (\text{species i energy consumption} \times \text{emission factor i}) \]

- **Emissions from other sectors (excluding power sector)**
  \[ \text{Emissions from other sectors (excluding power sector)} = \sum (\text{Non-power energy i consumption} \times \text{emission factor i}) \]

Emissions from the power sector is calculated by equation (2), the emissions caused by electricity consumption of other sectors are all included in the power sector. In addition to electricity, CO$_2$ emissions from other sectors are calculated by equation (3), excluding emissions from their electricity consumption.

In 2008, total CO$_2$ emissions of Guangdong province is about 0.53 billion tons. Among this the CO$_2$ emissions from power, industry, transportation, construction and agriculture sectors were 56%, 31%, 6%, 4%, and 3%, respectively (Figure 1-2-1). The emissions from power and industrial sectors are the largest and relatively concentrated.

![Figure 1-2-1 Sectoral emissions](image)

1) **Power Sector**

In 2008, CO$_2$ emissions from power sector accounted for 56% of the total CO$_2$ emissions of Guangdong province. 78% of the electricity in Guangdong was from thermal power, most of them
are from coal-fired power generation.

2) Industry Sector

Industry is a major energy consumer. If excluding CO₂ emissions generated by electricity usage, industry sector emission accounted for 31% of the total emissions of Guangdong, and is the second largest sector for CO₂ emissions. In the various industries, non-metallic (cement, ceramics, building materials, etc) industries emitted the largest amount of CO₂.

3) Building Sector

Buildings include commercial buildings, public buildings and residential buildings. Building sector emission mainly comes from electricity consumption. The CO₂ emissions from construction sector accounts for 5.7% (if excluding electricity usage) of the total CO₂ emissions of Guangdong province, and 14.7 (if including electricity usage). Electricity saving is the most important solution to reduce emissions from building sector.

4) Transportation Sector

In 2008, the CO₂ emissions from transportation sector reached 46 million tons, accounting for 9.1% of total annual emissions of Guangdong Province.

1.3 Major point sources of CO₂

1.3.1 General status

The electric industry of Guangdong has the characteristics as follows:

a) Large amount of emission and high rate of increase. The CO₂ emission from electricity sector has accounted for >50% of the total CO₂ emission in Guangdong in 2008. If simply calculating the emission amount by installed capacity, the CO₂ emission from power industry in 2008 has doubled than that in 2002.

b) Concentrated emission. In comparison to industry sector and transportation sector, the CO₂ emission from electric industry is much more concentrated. Therefore, it is easier to implement comprehensive management, to eliminate the out-of-dated capacity, and to apply CO₂ emission reduction measures in power industry.

c) Coal and oil are the main fuels. The installed coal fired power capacity accounts for >78% of the total capacity. The proportion of low-carbon power is low. The carbon emission factor for electricity industry is about 222.95 g/kWh, which is much higher than that in developed countries (100 to 150 g/kWh). Therefore, coal fired power plants dominated power sector is major reason of the high CO₂ emissions in the power sector of Guangdong.

In conclusion, the power sector is the largest CO₂ emitter in Guangdong. It will be the main carrier of the application of CCS-related technologies such as CCS, CCR and CCUS in the future. Therefore, this study mainly investigates the data of the emission point sources of the electric industry of Guangdong Province, and also considers other major emission sources including steel and petrochemical industries.

1.3.2 Distribution of major point sources

Major point sources (MPS) of CO₂ emission from the electric sector in Guangdong are
mainly located in the economically developed regions of the pan-Pearl River Delta Region, especially in Dongguan, Guangzhou, and Shenzhen. Secondarily, the carbon emission sources in Jiangmen and Shantou are also high. The MPS of steel industry mainly reside in Shaoguan, Guangzhou, and Zhuhai; while those of petrochemical industry are mainly in Guangzhou, Maoming, and Huizhou (Fig. 1-3-1).

The economic development is in high lever in Pearl River Delta Region, and the requirement of high-quality environment in this region will rise considerably in the near future. Therefore, reducing the carbon emission and optimizing the environment of this region are the key tasks of Guangdong Province in the near future.

1.3.3 Point source emissions calculation

1) Methodology of calculating emission from MPS

The total CO₂ emission from MPS is calculated by the energy consumption multiplying the emission factors that IPCC recommended:

\[ \text{Point source emissions} = \sum (\text{energy consumption from point sources} \times \text{emission coefficient}) \]

The energy consumption from the power industry was calculated from the designed standard coal consumption for power generation based on the data from the China Southern Power Grid, while the energy consumption from the steel and petrochemical industry was from statistic of industry associations.

2) MPS in power industry

The fuel consumption categories, locations and emissions of MPS have been studied. Data covering the whole generation from power industries access to Guangdong Grid, except those small thermal power plants not included into the grid. Emissions from the thermal power plants within the grid occupied 79% of the total emission of electric power industry in Guangdong (Fig. 1-3-2).
Figure 1-3-2  The percentage of CO₂ emissions of major point sources of the electric sector

The classification and emissions of different generators are shown in Table 1-3-1. The total installed capacity of the major point sources is about 40 MKW. The emission from coal-electricity accounts for the major part of the emissions. The installed capacity of these MPS occupied 66% of the total electric power industry in Guangdong, in which the generators with installed capacity >60 MW occupied 39% of total point source installed capacity.

Table 1-3-1  The structure of generators of electricity point source*

<table>
<thead>
<tr>
<th>Generator type</th>
<th>Installed capacity</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal-fired Power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ultra-supercritical unit</td>
<td>≥60 MW</td>
<td>39%</td>
</tr>
<tr>
<td>supercritical unit</td>
<td>30-60 MW</td>
<td>22%</td>
</tr>
<tr>
<td>sub-critical unit</td>
<td>20-30 MW</td>
<td>2%</td>
</tr>
<tr>
<td>sub-critical unit</td>
<td>12.5-20 MW</td>
<td>2%</td>
</tr>
<tr>
<td>Combined Heat and Power</td>
<td></td>
<td>11%</td>
</tr>
<tr>
<td>Comprehensive utilization</td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>Gas-fired Power</td>
<td></td>
<td>16%</td>
</tr>
<tr>
<td>Oil-fired Power</td>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

* Data source: China Southern Power Grid and industry statistics
Chapter 2

CO₂ Storage potential in and offshore Guangdong

As in PACOS-GD project the inland basins are proved with little capacity, and the Pearl River Mouth Basin has been studied, during this period we concentrated to the study of the Beibuwan, Qiongdongnan, and Yinggehai basins (Fig. 3-1).

![Figure 2-1. The sedimentary basins to be assessed in the Task #2 for CO₂ storage capacity. Data points and geological sections are shown.](image)

2.1 Beibuwan basin

2.1.1 General geology

The Beibuwan Basin (BBWB) is a Cenozoic basin developed in the northwestern South China Sea. It major portion resides in the Beibu Gulf with water depth shallower than 55 m, but also bestride the Leiqiong peninsula of the Guangdong province (also called as the Leiqiong Basin), and extends to the northern Hainan Island (the Fushan sag), with a total area of 120,000 km² (Fig. 2-1). In some literatures, the name of Beibuwan Basin refers only to the offshore portion within the Beibu Gulf, with an area of 38,000 km².
The BBWB is a Cenozoic rifted basin formed on a basement of Paleozoic foldbelt. It experienced three episodes of rifting in Late Cretaceous or Paleogene, Eocene, and late Eocene to Oligocene. In Neogene the entire basin subsided, discrete rifts united and accepted marine sedimentation.

### 2.1.2 Stratigraphy

Cenozoic sediments in the BBWB may reach a thickness of 7 km (Fig. 2-1-1) (康西栋 et al., 1994). The Paleogene syn-rift sequence consists of mainly continental clastic sediments, while the Neogene post-rift sequence consists of mainly littoral and shallow marine sediments (Fig. A-2).
2.1.3 Structure and stability

The BBW basin is generally NE-running basin, with a two-layer structure typical for rift basins, a syn-rift lower layer of discrete grabens and half grabens, and a post-rift upper layer of saucer-like downwarps. The two layers are separated by a significant regional unconformity (Fig.). The basin is divided into 7 sags and 3 uplifts according to the thickness variation of the Paleogene layer.

The basin is relatively stable during the Neogene period, but in Quaternary time the area was activated with strong basaltic activity and earthquakes. Quaternary basalts cover large areas in the Leizhou peninsula and northern Hainan Island. Strong earthquakes occurred near the Qiongzhou Strait, including the M7.5 Qingshan earthquake in 1605, and the two M6 East Beibu Gulf earthquakes in 1995 (魏柏林等, 2001). But the volcanic and earthquake activities are weak within the central offshore portion of the basin (Fig. A-3).

2.1.4 Geothermal status

The observed geothermal gradient in the BBWB is 32.7°C/km in average, with 38.6°C/km in the Wenxinan Sag, 33.5°C/km in the Haizhong Sag, 35.0°C/km in the Wushi Sag, and 32.5°C/km in the Maichen-Haitoubei Sag. The heat flow in the basin is 61.7 mW/m² in average, with 64.6 mW/m² in the Wenxinan Sag, 52.2 mW/m² in the Haizhong Sag, 61.9 mW/m² in the Wushi Sag, and 58.8 mW/m² in the Maichen-Haitoubei Sag (康西栋 et al., 1995).

2.1.5 Petroleum Geology

The hydrocarbon exploration in the BBWB started in late 60s of the last century. In addition to Chinese companies, companies such as Amco, Sun, Total, Kosan, BP have been involved in the exploration activities in the basin. So far more than 120 wells have been drilled, 8 oil fields offshore and several oil-bearing structures onshore have been found, with a total discovered reserve of 130 Mt oil and 7 Bcm gas by 2006. The latest estimations for reserves are 730 Mt oil and 60 Bcm gas (Zhang et al., 2007).
Two sets of source rocks developed in the basin. The lacustrine dark mudstone in the Eocene Liushagang Formation has a thickness up to >1000 m and is the main source, and the Oligocene Weizhou Formation and upper Liushagang Formation contain source rocks locally (朱伟林 et al., 2004).

Three source-reservoir-seal assemblages developed in the basin: 1) the self-contained assemblage within the Eocene Liushagang Formation; 2) the source in Eocene Liushagang Formation, and reservoir-seal in the Weizhou and upper formations; 3) the source in Eocene Liushagang Formation, reservoirs in the fissured Paleozoic basement highs, and seals in the mudstones overlying the reservoirs (张启明 and 苏厚熙, 1989).

### 2.1.6 Conditions for CO₂ storage

There are 3 sets of seal-reservoir assemblage in the basin. The mudstone in the post-rift Middle Miocene Jiaowei Formation forms the shallowest regional seal. The shallow lake mudstones in the sun-rift Oligocene Weizhou Formation and the 2nd member of the Eocene Liushagang Formation forms deep regional seals. The Paleogene sandstone layers and the fractured Carboniferous limestone in buried basement hills contain reservoirs (李国玉等, 2002).

#### Table 2-1-1. Area and sediment thickness of the structural divisions in the Beibuwan Basin (金庆焕等, 1989)

<table>
<thead>
<tr>
<th>Structure Unit</th>
<th>Area /km²</th>
<th>Neogene Thickn. /m</th>
<th>Paleogene Thickn. /m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weixinan Sag</td>
<td>3000</td>
<td>1200</td>
<td>8000</td>
</tr>
<tr>
<td>Haizhong Sag</td>
<td>2900</td>
<td>2200</td>
<td>8000</td>
</tr>
<tr>
<td>Haitoubei Sag</td>
<td>3900</td>
<td>1500</td>
<td>4000</td>
</tr>
<tr>
<td>Wushi Sag</td>
<td>2800</td>
<td>2200</td>
<td>7000</td>
</tr>
<tr>
<td>Maichen Sag</td>
<td>2600</td>
<td>1500</td>
<td>5500</td>
</tr>
<tr>
<td>Fushan Sag</td>
<td>3000</td>
<td>1500</td>
<td>5000</td>
</tr>
<tr>
<td>Leidong Sag</td>
<td>6100</td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>Qixi Uplift</td>
<td>5100</td>
<td>1800</td>
<td>500</td>
</tr>
<tr>
<td>Liushagang Uplift</td>
<td>1000</td>
<td>1200</td>
<td>500</td>
</tr>
<tr>
<td>Lingghao Uplift</td>
<td>1100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 2-1-2. Parameters of sedimentary strata in the Beibuwan Basin

<table>
<thead>
<tr>
<th>Sag</th>
<th>Formation</th>
<th>Porosity (%)</th>
<th>Permeability (mD)</th>
<th>Depth (m)</th>
<th>Thickness (m)</th>
<th>Area (km²)</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weixinan</td>
<td>Liushagang, 3rd member</td>
<td>5.16~25.21, Av. 9.96</td>
<td>0.3~330, Av.44.52</td>
<td>1800~2100</td>
<td>94</td>
<td>3000</td>
<td>(郭爱华 et al., 2010; 郭飞飞 et al., 2009)</td>
</tr>
<tr>
<td></td>
<td>Liushagang, 1st member</td>
<td>26.65~29.74, Av. 28</td>
<td>423~673, Av.534</td>
<td>1500</td>
<td>219</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weizhou</td>
<td>23.32~30, Av. 27.5</td>
<td>234.7~689.11, Av.511</td>
<td>1300</td>
<td>85.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maichen</td>
<td>Liushagang</td>
<td>5.1~11.3, Av 7.5</td>
<td>0.244~1.78, 0.73</td>
<td>100~2000</td>
<td>215</td>
<td>2600</td>
<td>(苏永进 et al., 2009)</td>
</tr>
<tr>
<td></td>
<td>Weizhou</td>
<td>15~25</td>
<td>1~760</td>
<td>2000</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haizhong</td>
<td>Liushagang</td>
<td>7.8</td>
<td>0.4~3</td>
<td>2000~4000</td>
<td>126</td>
<td>2900</td>
<td>(孙建峰 et al., 2009)</td>
</tr>
<tr>
<td></td>
<td>Weizhou</td>
<td>20~24</td>
<td>230~610</td>
<td>1000~2000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 2.1:

<table>
<thead>
<tr>
<th>Location</th>
<th>Member</th>
<th>Age (Ma)</th>
<th>Thickness (m)</th>
<th>Sediments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fushan</td>
<td>Liushagang, 1&lt;sup&gt;st&lt;/sup&gt; member</td>
<td>10~13</td>
<td>0.16~500</td>
<td>2500~400</td>
</tr>
<tr>
<td></td>
<td>Liushagang, 3&lt;sup&gt;rd&lt;/sup&gt; member</td>
<td>13~18</td>
<td>1~1600</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weizhou</td>
<td>5.2~33</td>
<td>0.04~6930</td>
<td>1000~2500</td>
</tr>
<tr>
<td>Leidong</td>
<td>Weizhou, Liushagang</td>
<td>13~17</td>
<td>44~188</td>
<td>1300</td>
</tr>
<tr>
<td>Wushi</td>
<td>Weizhou, Liushagang</td>
<td>15~25</td>
<td>1~760</td>
<td></td>
</tr>
</tbody>
</table>

### 2.2 Qiongdongnan basin

#### 2.2.1 General geology

The Qiongdongnan Basin (QDNB) lies in 111°30′~109°0′E and 18°30′~16°30′N with a total area of 41 300 km<sup>2</sup>. The QDNB is a Tertiary basin developed on the northwest margin of the South China Sea. Its basement is composed of Mesozoic granites and Paleozoic metamorphic and sedimentary rocks. Above the basement the depressions are aligned in three NEE-running belts: the northern, the central, and the southern depressions belts. The depression belts are separated by two belts of uplifts (Fig. 2-1 and 2-2-1).

![Geological sections across Yinggehai and Qiongdongnan Basins](image)

**Figure 2-2-1** Geological sections across Yinggehai and Qiongdongnan Basins. For locations see Fig. 2-1.

The QDNB experienced two episodes of rifting: from Eocene to early Oligocene and during late Oligocene. Two styles of structures, half-graben and graben, developed in zonation from north to south and segmentation from east to west. In Neogene the QDNB evolved to a post-rifting downwarped basin and filled with thick sediments.

In the Qiongdongnan basin, the basement depth is deeper in the west than that in the east. The depth for the central depression ranges from 7 km to 12 km. Of this suite sediments, 9 sequences can be recognized from the basement to the top. In rifting stage, the development of sequence was mainly controlled by episodic extension, and the sequence consists of coarse clastic
sediments deposited in alluvial, lacustrine, fan-delta and littoral environments. In the post-rifting stage, the formation of sequence was mainly controlled by global change of sea level, and the sequence is characteristic of typical passive continental margin and includes lower system tracts, progressive system tracts and high system tracts.

In the QDNB the geothermal gradient is 37.4 °C/km in average, and seafloor temperature is 20 °C in average (Gong and Li, 2004).

### 2.2.2 Stratigraphy

A composite stratigraphic column is presented in Fig. 2-2-2.

<table>
<thead>
<tr>
<th>System Period</th>
<th>Chrono-stratigraphy</th>
<th>Relative Eustasy</th>
<th>Sedimentary Environment</th>
<th>Tectonic deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pliocene</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miocene</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oligocene</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Eocene</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2-2-2** Composite stratigraphic column for the Qiongdongnan and Yinggehai basins.
2.2.3 Petroleum Geology

The Qiongdongnan Basin (QDNB) experienced three tectonic evolutionary stages: rifting, post-rifting and tectonic reactive stage. The rifting occurred from Eocene to Low Miocene and formed the major source rocks in the study area, which are composed of the dark mudstones of the Oligocene Yacheng Fm., deposited in Land-Sea transitional environment and the mudstones of the Low Miocene Lingshui formation deposited in bathyal environment (Li et al, 2007). In post-rifting stage from the Lower to Middle Miocene the basin was filled with fluvial-deltaic and shallow marine clastic deposits which contain important reservoirs. In the last stage, the basin was filled with neritic, slope and abyssal deposits and formed the basin-wide caprocks (He et al, 2002).

In the QDNB three source-reservoir-seal assemblages have been identified (Dong, 1999; Wan et al, 2007; Yuan et al, 2009): (1) the Oligocene Lingshui Fm. self-containing assemblage; (2) the Miocene assemblage with source rocks in the Yacheng and Lingshui Fms. locally deposited in sags, sandstones reservoirs of neritic environment in Lingshui and Sanya Fms., and caprocks in upper Yinggehai Fm.; (3) the central canyon assemblage filled with sandstones of turbidite channel and mass transport complex together with Yinggehai Fm. mudstones as the seal, which is now expected as the most prospective region.

A big gas field YA13-1, a gas field YA13-4 have been found. Oil/gas shows have been found in Yacheng, Baodao, Songtao sags and Songtao uplift (Huang, 1999). The latest estimations for reserves are 272 Mt oil and 1114 Bcm gas (Zhang et al., 2007).

2.2.4 Geological conditions for CO₂ storage

Regional seals are the mudstone layers of Shanya, Meishan and Yinggehai Fm, which covered almost the entire basin except the northern slope and central uplift. Taking northern Yacheng sag for example, YC8-2-1 well exhibits that the mudstones content in the Miocene Sanya Fm. reaches 44.1-57.4%, with over 650m thick, and in the Meishan Fm. it reaches even up to 91.4%. The Pliocene Yinggehai Fm. contains 73.8% mudstone with thickness of 1120m (Wang and He, 2003).

Favorable reservoirs in the QDNB can be divided into three types in terms of their sedimentary environment: fan delta, channel and gravity flow, reef and platform carbonates. Sandstones reservoirs have been found mostly in the Lingshui, Sanya and Huangliu Fm (Liu et al, 2006).

The principal sandstones reservoir are deposited in the delta front, such type accounts for 50-87 percent of the 3rd member of Lingshui Fm., and have porosity of 7.2%-15.7% and permeability of 0.4-333 md (Yang, 2008).

The second most important reservoir associated with gravity flow accumulated in Miocene Huangliu and Yinggehai Fms including slope, basin floor, turbidite channel and mass transport complex and displayed good porosity and permeability (Table 1). For example, seven sandstones layers of basin floor and turbidite channels have been penetrated by Well LD30-1-1A; a single layer which ranges from 18.6 to 87m thick has porosity of 20% and permeability of 11.72md. The central canyon in the Qiongdongnan basin as a special sedimentary system is filled with fine-grained deposits with respect to turbidites, slumps and mass transport complex and can also been expected (Fu et al, 2009).
The third type is reservoirs associated with platform limestones and reef complexes of the Sanya Fm, its porosity and permeability can reach 24% and 3md respectively (Table 2-2-1).

### Table 2-2-1. Parameters of sandstones in the Qiongdongnan Basin (Wang and He, 2003)

<table>
<thead>
<tr>
<th>Well</th>
<th>Lithology and sedimentary facies</th>
<th>Porosity (%)</th>
<th>Permeability (md)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>Yinggehai Fm.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YC8-2-1</td>
<td>sandstones</td>
<td>30.4</td>
<td>20.4</td>
</tr>
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<td>YC13-1-4</td>
<td>sandstones</td>
<td>31.14</td>
<td>34</td>
</tr>
<tr>
<td>Ying9</td>
<td>sandstones</td>
<td>23.8</td>
<td></td>
</tr>
<tr>
<td>YC35-1-1</td>
<td>turbidite channel sandstones</td>
<td>14.8</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huangjilu Fm.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YC13-1-1</td>
<td>carbonate platform</td>
<td>21.14</td>
<td>2.52</td>
</tr>
<tr>
<td>YC13-1-2</td>
<td>carbonate platform</td>
<td>11.4</td>
<td>6.6</td>
</tr>
<tr>
<td>YC13-1-4</td>
<td>turbidite fan sandstones</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.5</td>
<td>15</td>
</tr>
<tr>
<td>YC35-1-2</td>
<td>turbidite channel sandstones</td>
<td>14.8</td>
<td>11.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td>10.5</td>
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<tr>
<td></td>
<td></td>
<td>17.1</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Meishan Fm.</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>YC7-4-1</td>
<td>shallow-water platform sandstones</td>
<td>7.52</td>
<td>2.68</td>
</tr>
<tr>
<td>Ying9</td>
<td>shallow-water platform sandstones</td>
<td>35.1</td>
<td>34.3</td>
</tr>
<tr>
<td>YC35-1-2</td>
<td>sandstones</td>
<td>15.1</td>
<td>15.1</td>
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<td>LS2-1-1</td>
<td>delta front sandstones</td>
<td>25.7</td>
<td>18.7</td>
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<td>BD19-2-1</td>
<td>sandstones</td>
<td>17</td>
<td>12.8</td>
</tr>
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<td></td>
<td>21.2</td>
<td>15.5</td>
</tr>
<tr>
<td>ST36-1-1</td>
<td>delta front sandstones</td>
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<td>17.25</td>
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<td>Sanya Fm.</td>
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</tr>
<tr>
<td>YC8-2-1</td>
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<td>19</td>
</tr>
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<td>YC14-1-1</td>
<td></td>
<td>23</td>
<td>21</td>
</tr>
<tr>
<td>YC7-4-1</td>
<td>coastal sandstones</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Ying9</td>
<td></td>
<td>23.8</td>
<td>5.8</td>
</tr>
<tr>
<td>YC13-1-4</td>
<td>channel sandstones</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>YC13-1-A8</td>
<td>channel sandstones</td>
<td>19.1</td>
<td>9.2</td>
</tr>
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<td>YC13-1-8</td>
<td>channel sandstones</td>
<td>17.6</td>
<td>6.9</td>
</tr>
<tr>
<td>YC21-1-1</td>
<td>channel sandstones</td>
<td>19.3</td>
<td>7.6</td>
</tr>
<tr>
<td>YC21-1-2/3</td>
<td>carbonate platform limestones</td>
<td>24</td>
<td>0.5</td>
</tr>
<tr>
<td>YC35-1-2</td>
<td>delta front sandstones</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>LS2-1-1</td>
<td>coastal sandstones</td>
<td>32</td>
<td>19.2</td>
</tr>
<tr>
<td>BD19-2-1</td>
<td>delta front sandstones</td>
<td>19.5</td>
<td></td>
</tr>
</tbody>
</table>
2.3 Yinggehai Basin

2.3.1 General geology

The Yinggehai basin (YGHB) lies at the most northwest portion of the South China Sea, with a total area of 127000 km². It is located in the seaward extension of the NW-running Red River Fault Zone.

The YGHB is a transtensional rift basin formed by a strike-slip movement of the NW-trending Red River Fault Zone during the Tertiary time. The controlling stress field of the basin changed during the different structural inversion.

The structure of the YGHB is relatively simple, composed of the NW-SE-running Central sag and a N-S-running Lingao uplift (Fig. 2-1). The Central Sag is the deepest one of northern margin of South China Sea. The maximum depth of basement reaches 17 km.

The Yinggehai basin is a young Cenozoic sedimentary basin with high geothermal and overpressure. The geothermal gradient is 36~44 °C/km and in average 42 °C/km. High heat flow appears in the diapir zone in the Central Sag. Seafloor temperature is about 20 °C (Gong and Li, 2004).

2.3.2 Stratigraphy

The YGHB shares the same stratigraphic divisions and nomenclature with that of the QDNB (Fig. 2-2-1), but the thickness and distribution are different.

2.3.3 Petroleum Geology

The tectonic evolution of the Yinggehai Basin (YGHB) is similar to that of the Qingdongnan Basin. The two basins use the same stratigraphic naming system as that shown in Fig. 2-1.

The YGHB is one of the most petroliferous basins in the northern continental shelf of the South China Sea. Until now, a number of commercial gas fields have been found, such as DF1-1, LD5-1, LD22-1 and LD8-1, most of which are developed on the top of diapiric structures (Zhu et al., 2004). The DF gas field was the largest gas field found in the basin. The hydrocarbon gas content in the Yinggehai basin ranges from 7.0% to 85%. The latest estimations for reserve is 1307 Bcm gas (Zhang et al., 2007).

The DF1-1 gas field is a large dome structure with area of 350 km² and amplitude of 255 m. It is cut by faults into the west and east blocks. Gas-bearing area is 288 km². Reservoir is the marine sandstone of the Upper Miocene Huangliu Formation at the depth of 1000~1350 m. Single-layer thickness 5~40 m, porosity 21~25%, permeability 3.6~275 mD, high temperature gradient (46.7 °C/km) and normal pressure. Proven gas reserve is 99.7 bcm. CO2 concentration is low (<1%) in the west block, but very high (55~71% in the east block (李国玉等, 2002).

Potential source rocks in the Yinggehai basins include the Yacheng, Sanya, and Meishan Fms. (Chen, 1990; Zhang et al, 1993; Hao et al, 1995; Gong and Li, 1997; Hao et al, 1998). The Yacheng Fm. with thick mudstones was deposited during the rift stage of the basin evolution, which has been confirmed to be the major source of the Yacheng gas field (Hao et al., 1998). The Sanya and Meishan Fms. are mud-dominated units deposited in marine environments during the regional subsidence.

Due to sufficient sediment supply of the Red River, the Yinggehai basin developed fluvial, deltaic and shore-zone depositional systems, and formed basin-wide, thick reservoirs. Sandstones
deposited in fan delta, fluvial delta, neritic environment sever as the suitable reservoir in the Lingshui Fm, so do the sandstones deposited in turbidite current, neritic and bathyal environment in Sanya, Huangliu and Yinggehai Fm (Gong and Li, 1997).

Generally, the petroleum system in the Yinggehai basin is divided into two groups: (1) source rocks in Shanya and Meishan Fm accompanying with sandstones in the upper Meishan, middle Yinggehai and Huangliu Fms sealed by mudstones of upper Yinggehai and Huangliu Fms; (2) source rocks in the lower Yinggehai and Huangliu Fms covered by middle sandstones and upper mudstones (Xu and Wan, 2008).

Structures associated with diapir not only served as the major hydrocarbon migration pathways but also provided the best place for gas accumulation (He et al, 1994; Zhang et al, 2004).

2.3.4 Geological conditions for CO₂ storage

The Yinggehai basin is characterized by high subsidence rate (500-1400m/Ma), and the maximum thickness of Cenozoic is over 17km. Due to the rapid loading and undercompaction, as well as hydrocarbon generation and thermal expansion of pore fluids, strong overpressures developed over a large part of the basin (Gong and Li, 1997; Zhang and Li, 2000). Recent exploration confirmed that an overpressured system exists in the central part of the Yinggehai basin, with the maximum pressure coefficient of 2.1 and concentrated in the section of Sanya Fm-Lower Yinggehai and Huangliu Fm. Overpressure and diapiric structure may lead to the failure of the CO₂ storage, and even trigger geological disaster, therefore, diapiric structure and pressure investigation become very necessary in Yinggehai basin.

Frequent cyclic sealevel changes in the Yinggehai basin produced a large amount of local caprocks, the 1st member of Sanya to Meishan to Yinggehai and Huangliu Fms are all rich in abyssal mudstones (Gong and Li, 1997).

Potential reservoirs in the Yinggehai basin include deltaic, channel, neritic, turbidites sandstones. Sandstone reservoirs have been found mostly in Lingshui, Sanya, Huangliu and Yinggehai Fms. For example, the well LD30-1-1 (A) has penetrated 4 layers sandstones with total thickness of 361m, deposited in the gravity flow channel (Gong and Li, 1997). Coastal sandstones in the Yinggehai Fm. show good porosity and permeability (Table 2-3-1).

<table>
<thead>
<tr>
<th>Well</th>
<th>Formation</th>
<th>Sedimentary facies</th>
<th>Lithology</th>
<th>Porosity (%)</th>
<th>Permeability (md)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LG20-1-1</td>
<td>3432-3803m</td>
<td>delta</td>
<td>sandstone</td>
<td>13-15</td>
<td></td>
</tr>
<tr>
<td>LT1-1-1</td>
<td>Yinggehai</td>
<td>coastal</td>
<td>sandstone</td>
<td>25</td>
<td>600</td>
</tr>
<tr>
<td>HK30-3-1A</td>
<td>Yinggehai</td>
<td>coastal</td>
<td>sandstone</td>
<td>21.5</td>
<td></td>
</tr>
<tr>
<td>LD15-1-1</td>
<td>Yinggehai</td>
<td>neritic</td>
<td>fine grained sandstone</td>
<td>30</td>
<td>800</td>
</tr>
<tr>
<td>LD15-1-1</td>
<td></td>
<td>turbidite fan</td>
<td>fine grained sandstone</td>
<td>&lt;20</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2-3-1 Parameters of sandstones in the Yinggehai Basin
2.4 Early opportunity for CO\textsubscript{2} storage

Together with the experts in the CNOOC Shenzhen Branch, we have selected the LF2G1 structure as a potential site for CO\textsubscript{2} storage. The LF2G1 structure is a fault-bounded dome in the middle of the Lufeng Sag of the Zhu I depression, the PRMB. One well was drilled and proved to be dry. Relevant data from the LF2G1-1 well and 2D seismic survey were provided by CNOOC. Preliminary analysis of LF2G1 is on the way.

2.4.1 Geological setting

The Zhu I depression is a petroliferous depression in the northern depression belt of the PRMB. It has an area of 31000 km\textsuperscript{2}, sediment thickness up to 8500 m, including Paleogene up to 5100 m and Neogene up to 3700 m (苏乃容 et al., 1988).

Paleogene sedimentation was continental infilling of rifts, consists of the Paleocene Shenhu Formation of volcanic-rich clasts, Early Eocene Wenchang Formation of lacustrine coal-bearing dark mudstone, Late Eocene to Early Oligocene Enping Formation of intercalated fluvial sandstone, siltstone, and mudstone with coal seams, and Late Oligocene Zhuhai Formation of sandstone and mudstone of alternative continental and marine facies. Neogene wide-spread marine sedimentation consists of Miocene Zhujiang, Hanjiang, and Yuehai formations of shelf and deltaic sediments with carbonate in the uplifts, and the Pliocene Wanshan Formation calcareous mudstone and sandstone (苏乃容 et al., 1988).

The thick neritic mudstones in Early-Middle Miocene Zhujiang and Hanjiang formations form excellent regional seal. A stable mudstone layer of 22~220 m in thickness characterizes the top of the Hanjiang Formation, and a stable mudstone layer of 50~70 m in thickness characterizes the top of the Zhujiang Formation (卢广智 et al., 1988).

The Zhu I depression consists of 5 sags: from SWW to NEE, the Enping, Xijiang, Huizhou, Lufeng, and Haifeng sags.

The Lufeng Sag lies in the central segment of the Zhu I depression and has an area of 2540 km\textsuperscript{2}. It consists of 4 simple rifts with boundary faults dipping southwards (卢广智 et al., 1988). 4 wells drilled within the sag found no oil/gas show. The lack of source is believed the reason. The Paleogene mudstones in the sag contain TOC<0.6% (苏乃容 et al., 1988). Although oil fields have been found in the Huizhou Sag to the west and in the northern Dongsha Uplift to the south, the hydrocarbons apparently did not migrate to the Lufeng Sag.

2.4.2 Structure

The LF2G1 is a NEE-elongated dome cut by faults into A and B blocks. The maximum amplitude is 110 m and 150 m for the A and B blocks respectively (Fig. 2-4-1).
The LF1G1-1 well was drilled near the center of A block at water depth of 96 m. It was terminated at 2483.5 m with no oil/gas show. Tertiary mudstones in the LF2G1-1 well has TOC <0.4%. The absence of source rocks in and adjacent the trap is believed the main reason for its lack of oil. However, this might be advantageous for the trap to become an early opportunity for CO$_2$ storage, if we do not want to conflict the ongoing hydrocarbon exploration in the PRMB.

2.4.3 Stratigraphy
The LF2G1-1 well encountered the Pliocene Wanshan Formation, Miocene Yuehai, Hanjing, and Zhujiang formations, and Oligocene Zhuhai and Enping formations. It penetrated the basement of pre-Cenozoic gneiss at 2450 m.

2.4.4 Conditions for CO$_2$ storage
The Hanjiang and Upper Zhujing formations above the T50 interface (top lower Zhujiang Formation) at 1967m depth are composed of mainly mudstone and form good seal, while the strata bellow T50 are rich in sandstone and form multi-layered reservoir (Fig. 2-4-2).

The best reservoir-seal assemblage is in the lower Zhujiang Formation at depth of 1970~2043 m. It is composed of 73 m sandstone reservoir overlain by 51m mudstone caprock. The reservoir has single-layer thickness of 2.5~29.5 m, net/gross ratio of 0.87, porosity of 9.2-31.5%, and permeability of 560 mD.

A deeper reservoir is the sandstone in the Upper Oilcocene Zhuhai Formation at depth of 2142-2262 m. The reservoir has a total thickness of 120m, single-layer thickness of 4–16.5 m,
net/gross ratio of 0.84, porosity of 22-30%, and permeability of 716 mD.

The average geothermal gradient in the LF2G1-1 well is 30.6°C/km, and seafloor temperature is 21°C. Thus the CO₂ density at the 2000 m is 0.55 t/m³.

The estimated gas reserve of the LF2G1 is 153 Gm³ with gas volume factor of 0.004. Assuming all the pore volume may be replaced by CO₂ and the density of CO₂ is 0.55 t/m³, the estimated storage capacity is 153*10⁹*0.004*0.55 = 337 MtCO₂.

2.4.5 Questions to be answered

At this stage of preliminary assessment, still the following questions to be answered:

1) The seal of the deeper reservoir. This 120 m sandstone reservoir is overlain by 96.5 m alternative mudstone and sandstone, in which the mudstone proportion (in thickness) is 48%, and single-layer thickness is 1~6 m. In the lower portion of this segment there is a 9.5 m thick layer of sandstone with porosity of 29.4%. The questions are: if these 96.5 m sediments may be served as a seal for the deeper reservoir, and, if other sandstone layers should be considered as reservoirs?

2) The sealing property of the boundary faults is to be evaluated.

3) The storage capacity should be re-calculated according to the newly defined reservoirs.
References for Chapter 2


石彦民, 刘菊, 张梅珠, 陈达贤 and 马庆林, 2007. 海南福山凹陷油气勘探实践与认识. 南海地震, 27(03), 12.


孙建锋, 须雪华 and 席敏红, 2008. 北部湾盆地海中凹陷油气成藏条件分析. 海洋石油, 28(02), 4.

张启明 and 苏厚熙, 1999. 北部湾盆地石油地质. 海洋地质与第四纪地质, 9(03), 10.

李立新, 1999. 南海雷东凹陷区油气地质条件及勘探前景. 石油实验地质, 21(04), 5.

苏永进, 唐跃刚, 石胜群 and 房新娜, 2009. 北部湾盆地迈陈凹陷东部地区油气成藏特征. 石油与天然气地质, 30(02), 5.

黄志超, 2003. 北部湾盆地徐闻区块石油地质条件与油气远景. 海洋石油, 23(S1), 4.


Chapter 3

CCS Cost estimation

3.1 Major CO₂ point sources in Guangdong

The focus of our work is on the large, stationary CO₂ emitters, such as power plants, cement kilns, steel mills, and petroleum and chemical refineries. The goal has been to compile an initial database that represents the majority of large point source emissions that emit at least 100,000 tonnes of CO₂ per year. Sources smaller than these are considered unlikely to be economic to mate with CO₂ capture technologies, particularly in the nearer term. As a result, the analysis does not consider all anthropogenic CO₂ emissions, and specifically not those from small industrial CO₂ point sources (those emitting less than 100 ktCO₂/y), transportation, direct energy use in commercial and residential building sectors, land use, agriculture, and similar activities.

3.1.1 Data Collection

CO₂ emission data sources are coming from all kinds of source, including, CARMA, website of the economic & trade commission of China, IEA greenhouse gas inventory database, Ministry of Commerce of the People’s Republic of China, major industries annual report, and annual report of electric power, annual statistic report of provinces, Wanfang economic & enterprises database, Inventories of metallurgy enterprises and organization, annual report of steel & iron industry, inventory and database of cement enterprises, annual report of oil and chemical companies. Information centre of fertilizer, website of enterprises, and so on. Differential data sources, published data of data, calculation method and emission factors may cause some discrepancies among different statistics, which will be improved and optimized in the further investigation and research.

3.1.2 Methodology

CO₂ emissions calculation methodology is based on IPCC Guidelines for national greenhouse gas inventories (Houghton, 1997). Calculation methods were estimated based on available plant capacities and productivities, as noted below:

\[
(ECO_2)_{ji} = (EF)_{ji} \times (P_1)_{ji} \tag{1}
\]

\[
(ECO_2)_{ji} = (EF)_{ji} \times (P_2)_{ji} \times (A)_{ji} \times (T)_{ji} \tag{2}
\]

\[
(ECO_2)_{j} = \sum_{i} \sum_{j} (ECO_2)_{ji} \tag{3}
\]

Where, \((ECO_2)_{ji}\)- the estimated annual CO₂ emissions of \(i^{th}\) CO₂ emission source within \(j^{th}\) industry sector ; \((EF)_{ji}\)-Emission factor of \(i^{th}\) CO₂ emission source within \(j^{th}\) industry sector; \((P_1)_{ji}\)-Production yield of \(i^{th}\) CO₂ emission source within \(j^{th}\) industry sector; \((P_2)_{ji}\)-Productive capacity

1 This 100,000 tonne/yr threshold has been applied in similar studies for other regions of the world, including North America (see Dahowski et al. 2005), Europe (see IEA GHG 2005), and others.
of $i^{th}$ CO$_2$ emission source within $j^{th}$ industry sector; $(A)_{ji}$ -Productive rate of $i^{th}$ CO$_2$ emission source within $j^{th}$ industry sector; $(T)_{ji}$ -Full load time (hour) of $i^{th}$ CO$_2$ emission source within $j^{th}$ industry sector. CO$_2$ emission of power plant is based on product (Cement, Refineries, Steel & iron, Ammonia), productive capacity (power plant, Hydrogen), and mixture of them (Ethylene oxide, Ethylene). Table 3.1.1 shows CO$_2$ emission factor applied to each of these sectors (Houghton, 1997, Hendriks, 2002). It is estimated that the CO$_2$ sources estimates for the non-power sectors are current to at least 2004. Results for the non-power sectors indicate that there are 970 large (>100ktCO$_2$/yr) plants, emitting a combined 1,158 MtCO$_2$/yr. The majority (55%) are cement plants, followed by ammonia, iron & steel, and refineries.

Emission factor (EF) is the function of many factors, such as, fossil fuel type, efficiency of fuel combustion, process of industry, level of technology, degree of emission reduction, progress of technology, and so on. However activities of energy system are enormous and distributed everywhere. We only use product quantity and productive capacity. This CO$_2$ emission source statistics are not including Taiwan, Hong Kong, and Macao, and only focusing on industry sectors in China mainland.

Table 3.1.1  Emission factors of different CO$_2$ emission source

<table>
<thead>
<tr>
<th>Sector</th>
<th>CO$_2$ Emissions Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kt/kt)</td>
<td>0.882$^a$ 0.867$^b$ 1.111$^c$ 1.102$^d$</td>
</tr>
<tr>
<td>Power plant (kt/Gw.h)</td>
<td>1.0$^e$ 0.5$^f$ 0.4$^g$</td>
</tr>
<tr>
<td>Steel &amp; Iron (kt/kt)</td>
<td>1.270</td>
</tr>
<tr>
<td>Refineries (kt/kt)</td>
<td>0.219</td>
</tr>
<tr>
<td>Ethylene (kt/kt)</td>
<td>2.541</td>
</tr>
<tr>
<td>Ammonia (kt/kt)</td>
<td>3.800</td>
</tr>
<tr>
<td>Ethylene Oxide (kt/kt)</td>
<td>0.458</td>
</tr>
<tr>
<td>Hydrogen (kt/kt)</td>
<td>6.150</td>
</tr>
</tbody>
</table>

$^a$Dry Process1; $^b$Dry Process 2; $^c$Wet Process 1; $^d$Wet Process 2
$^e$coal power plant; $^f$gas power plant; $^g$oil comb, turbine or internal combustion.

3.1.3 Characteristics of Large CO$_2$ Point Sources in GD

Figure 3-1-1 shows the positions of emission sources, each of which has an annual emission more than 0.1 Mt. There are 158 such emission sources, and their total annual emissions are up to 324.73 Mt. Most of these sources locate in the area around Guangzhou.

Table 3-1-2 indicates the basic situation of emission sources in major CO$_2$ emission industries. Major CO$_2$ emission industries in GD are power plant, cement, iron & steel, ammonia ethylene, hydrogen, oil refining and ethylene oxide. Among these point emission sources, the power plants, releasing the most annual emissions, and naturally are also the main targets of CCS technology, followed by cement and iron & steel industries.
Figure 3-1-1 The type and distribution of large-scale CO₂ point sources in Guangdong

Table 3-1-2 The emissions of major CO₂ emission industries in Guangdong (Mt/a, 2008)

<table>
<thead>
<tr>
<th>Industry</th>
<th>Power plant</th>
<th>Cement</th>
<th>Steel &amp; Iron</th>
<th>Refinery</th>
<th>Ammonia</th>
<th>Ethylene</th>
<th>Hydrogen</th>
<th>Ethylene Oxide</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions</td>
<td>214.44</td>
<td>58.64</td>
<td>36.39</td>
<td>7.54</td>
<td>1.23</td>
<td>5.02</td>
<td>1.27</td>
<td>0.2</td>
<td>324.73</td>
</tr>
<tr>
<td>No. of emission sources</td>
<td>48</td>
<td>72</td>
<td>5</td>
<td>18</td>
<td>4</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>158</td>
</tr>
</tbody>
</table>

Power generation accounts for 66.04% of the total annual CO₂ emissions from all of these sources, and the vast majority of the power sector emissions are from coal-fired units. Cement plants contribute 18.06% of the total annual CO₂ emissions, as shown in Figure 2, followed by Iron & Steel, Refineries, Ethylene, Hydrogen, Ammonia, and Ethylene Oxide.

Figure 3-1-2 The proportion of CO₂ emissions from all sectors to total.

3.2 Economic of CCS in GD
3.2.1 Methodology for CCS cost calculation

**CO₂ Capture Costs**

The cost of capturing CO₂ from the flue gas or process stream of each identified source and the costs associated with dehydrating and compressing captured CO₂ to prepare it for pipeline transport are outside the scope of this particular study. Capture costs and compression and dehydration costs are therefore not included in the overall costs estimated for each source-reservoir pair. Future analyses will be able to integrate costs of CO₂ capture and compression and dehydration into the overall CCS project cost estimates.

**CO₂ Transport Costs**

**Pipeline Costs** – Capital costs associated with pipeline infrastructure development were calculated using the following relationship derived using multivariate regression analysis of recent 10 years of actual U.S. onshore natural gas pipeline costs reported to the Federal Energy Regulatory Commission (OGJ 2006).² All costs were adjusted to 2005 dollars, with high and low cost outliers for each size category excluded. Finally, empirical data on CO₂ pipeline flow rate and diameter from operating CO₂ pipelines in the U.S. was applied to develop the following pipeline cost algorithm:

\[
\text{Pipeline cost (\$)} = d \cdot 398,519 \cdot Q^{0.4055} + 466,464
\]

Where \(d\) is the pipeline length (in miles) and \(Q\) is the average annual CO₂ mass throughput (in MtCO₂/y).

For the purposes of this study, annual O&M costs are assumed to be 2.5% of capital, as suggested by McCollum and Ogden (2006) based on their review of a number of CO₂ transport studies, and similar to what has been applied in previous work (Dahowski et al. 2005).

**Pipeline Assumptions** – The base transport distance required for each source-reservoir pair is determined by the CO₂-GIS as the distance between them. To that straight-line distance, a 17% routing factor is added plus an additional 25 miles to allow for additional pipeline needed to access a suitable injection site within a given storage formation.³ Thus, a CO₂ source and storage reservoir that are co-located (distance from source to sink is zero miles) would still incur minimum transport costs associated with a 25-mile long pipeline. At this time no additional factors have been included to account for varying terrain or other cost impacts at this scale.

**CO₂ Storage Costs**

The costs assumed for drilling, completing, operating and maintaining CO₂ injection wells and oil and gas production wells (for EOR and ECBM) are based on the following. Note that, in

² Very little data on pipeline costs in China is available and therefore for the present study the application of U.S.-based costs have been adopted and assumed to represent a reasonable estimate at this time of expected costs for pipelines in China.

³ Note that this is greater than the 10-mile transport adder that has been applied previously for analyses in the U.S. (Dahowski et al. 2005). A larger 25-mile minimum pipeline distance was selected for this study due to the comparatively lower spatial accuracy for the CO₂ point source data and lower resolution of the candidate storage basin outlines that we have available for China.
all cases, vertical injection wells are assumed. Though directional wells have been used with great success by many hydrocarbon production projects as well as some early CCS projects, the performance and cost effectiveness of directional wells is highly project specific and difficult to generalize at this time for an assessment at this scale. It is worth noting however, that by assuming only vertical wells this analysis might be overestimating a portion of the resulting costs in the long term as directional drilling becomes common for CCS.

**Well Capital Costs** – Per-well capital costs are based on regression analysis of onshore oil and gas well drilling cost data reported by the 2003 Joint Association Survey on Drilling Costs and presented in Augustine et al. 2006. In order to account for recent increases in drilling costs beyond standard inflation, costs were escalated based on an index derived from a summary of historical drilling cost trends as reported by the EIA Annual Energy Review (2008).

Thus, well costs (for both production and injection wells) are estimated using the following expression:

\[
\text{Well cost (}$/\text{well}$) = 1,000,000 \times 0.1271e^{0.0008z} + 530.7z
\]

where \(z\) is the depth of the well, in meters.

**Other Injection Field Infrastructure** – Per-well field costs for flowlines and connections are estimated using the relationship presented by Bock et al. (2003) (presented here in 1999 dollars and then converted prior to use to 2005 dollars):

\[
\text{Per-well flowline & connection cost} = 43,600 \times (7,389 / (280n))^{0.5}
\]

where \(n\) is the number of wells in the field.

**Annual Wellfield O&M Cost** – Using annual costs presented in the same paper by Bock et al., for normal daily expenses, consumables, surface maintenance and subsurface maintenance (repair and services), the following relationship is used to estimate operating and maintenance costs for the project well-field:

\[
\text{Annual per-well O&M cost} = 24,600 + [13,600 \times (7,389 / (280n))^{0.5}] + [(5,000z) / 1219]
\]

where \(n\) is the number of wells, and \(z\) is the well depth, in meters.

### 3.3 Next steps

The main work next year is to analyze the transport and injection cost using above method. In this process, cooperation is needed from SCSIO about the formations information and from ERI about CO₂ point emission sources information.
Chapter 4

CO₂ Capture Ready Promotion

5.1 Identify power companies for CCR/CCS

We have begun to select some suitable power plants for the deployment of CCR/CCS. New power plants are our first choice, and the established large-scale power plants are our second consideration. Besides, there are some small-scale power plants, most of which used to burn heavy oil to generate electricity but were retrofitted to natural gas fuel. These small-scale power stations are also being considered at the moment. We comply with the following principles concerning the selection process:

a. the willingness of making power plants capture ready and retrofit to a carbon capture plant in the future;

b. the preferred scale of carbon capture of that plants would like;

c. the location of power plants;

d. the power generation technology in the plants.

We have obtained the list of will-be built power plants (Appendix I, at planning stage but might not yet gain NDRC approval), located them in our database and contacted some of the plants to express our interest. We learned that some of them have been approved by NDRC. At the moment we have chose three of them, following are their background information:

<table>
<thead>
<tr>
<th>Power Plants</th>
<th>Sanshui Hengyi Power Plant</th>
<th>Shenzhen Energy Binhai power plant phase I</th>
<th>CNOOC Huizhou refinery project phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>Baini Town, Sanshui District, Foshan City</td>
<td>Kuichong Town, Longgang District, Shenzhen City</td>
<td>Dayawan Petrochemical Industry Park, Huizhou City</td>
</tr>
<tr>
<td>Coordinates</td>
<td>23.02N, 112.84E</td>
<td>22.65N, 114.52E</td>
<td>22.75N, 114.59E</td>
</tr>
<tr>
<td>Scale</td>
<td>2×600MW SCPC</td>
<td>2×1000MW USCPC</td>
<td>10mt/y refinery &amp; 1mt/y ethene</td>
</tr>
<tr>
<td>Investment</td>
<td>5.6 bn RMB</td>
<td>8 bn RMB</td>
<td>51.7 bn RMB</td>
</tr>
<tr>
<td>Space</td>
<td>0.47 square km</td>
<td></td>
<td>2.68 square km</td>
</tr>
<tr>
<td>Scheme</td>
<td>1st unit on June 2010, 2nd unit on October 2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start Construct</td>
<td>June 2009</td>
<td></td>
<td>Under preparation</td>
</tr>
<tr>
<td>Remark</td>
<td>Boiler, turbine and generator were made by Shanghai Electric Group. The location for potential added capture unit has been suggested an a minor changes the chemical storage house might be adopted by the company for a 15% capture.</td>
<td>The power plant is currently waiting for NDRC approval.</td>
<td>The coal to hydrogen facility use coal (petro coke) as raw material to produce high concentrated hydrogen (98%), approximately 2.6 mt of CO₂ would be produced annually in the process. The power generation facility use coal to produce high-pressure steam which used to generate electricity and it is expected to emit 3.4 mt of CO₂ annually.</td>
</tr>
</tbody>
</table>

### 4.2 Case study of Shenzhen city

We evaluate the benefits of a ‘CCS Ready Hub’ approach, a regional ‘CCS Ready’ strategy, which not only includes a number of new coal-fired power plants but also integrates other existing stationary CO₂ emissions sources, potential storage sites and potential transportation opportunities into an overarching simulation model. A dynamic top-down simulation model was built based on economic decision criteria and option pricing theory. The model inputs and assumptions build on spatial sampling and analysis using a geographic information system (GIS) approach, engineering assessment of local projects and outputs of a CCS retrofitting investment evaluation through cost cash flow modelling. A case study of Shenzhen city in the Pearl River Delta area in Guangdong in southern China is presented, based on engineering and cost assessment studies and stakeholder consultations and building on existing geological surveys and infrastructure plans. The simulation results show that financing ‘CCS Ready’ at regional planning level rather than only at the design stage of the individual plant (or project) is preferred since it reduces the overall cost of building integrated CCS systems. On the other hand, we found the value of considering existing stationary CO₂ emissions sources in CCS ready design. Therefore, we recommended that making new plants CCS ready or planning a CCS ready hub should consider existing large emissions sources when possible.
Chapter 5

Energy-Carbon Control System Modeling

5.1 Overview of annual work and progress

ERI project team undertakes four tasks of the project as follows:

- Constituting CCS Evaluation Model of Guangdong Province
- Analyzing CCS Emission Reduction Potential of Guangdong Province
- Analyzing CCS Emission Reduction Cost of Guangdong Province
- CCS Technology Roadmap of Guangdong Province

According to the designing contents, the main task of ERI is to constitute the technology optimizing evaluation model of power sector in Guangdong Province, and estimate future potential of CCS technology under different scenarios in Guangdong Province through this model, and finally obtain CCS technology roadmap of Guangdong province with collaboration of other research groups.

For above tasks, ERI project team collected domestic and foreign relevant research materials and data. Some key issues including scenarios setting, model framework designing, model parameters structure, data availability, and study methodology are discussed inside ERI project team and with other research groups. ERI team also consults with other domestic and international research institutes and experts on this. As a result, the approach and output of ERI's work are further specified.

Based on previous work, ERI project team have preliminary constituted the framework of CCS technology and economy assessment model for Guangdong Province, and accomplished setting of some part of model parameters. However, the data on base year and calibration year are not obtained completely, and some technology parameters need to be further gathered and estimated. The preliminary model is still in construction and is expected to be finished by the end of 2010.

The work and activities have been done by now are summarized as follows:

1) Selected and determined relevant research model

ERI has worked at energy technology and policy evaluation for many years, and have developed several technology evaluation models. For the purpose of this project, AIM-Technology Model jointly developed by National Institute for Environmental Studies (NIES) and ERI is determined as the platform to constitute CCS technology and economy assessment model for Guangdong Province, by comparing the model framework, methodology, parameters structure and data requirement of different technology evaluation models.

2) Collected relevant research findings on future development of power demand of Guangdong Province

In order to analyze the development potential of CCS technology in Guangdong Province, the future energy demand of Guangdong Province will be first to analyzed. After a thorough discussion in the research group, the most important input parameter, i.e. future development of power demand in Guangdong Province, will be estimated on the basis of research results of other research projects and studies. ERI project team has exchanged opinions with other research groups.
and project teams, and obtained some findings of their researches on future development of power demand in Guangdong Province.

3) **Specified the scenario setting of the project**

Four scenarios are set to evaluate the development of CCS in Guangdong Province, i.e. baseline scenario, emission reduction scenario, policy scenario (including capture-ready policy), and high development of CCS scenario.

5.2 **Relevant works on model framework constitution**

To satisfy the project requirement, ERI project team made adjustments on technology categories and relevant parameters in the model. Some types power technologies were subdivided, while other types were merged (technologies with similar performance are classified one category), CCS relevant technology categories were added, and the model parameters reflecting policy and measures on CCS technology were added as necessary.

Energy technology evaluation model is a bottom-up optimized model based on plenty of energy technologies, thus relevant data related to technologies, costs and policies and measures are required to be collected during the establishment of model. Data collection has been in progress:

1) Data on energy consumption, power generation and carbon emissions of Guangdong Province were collected, analyzed and assessed. These include: energy consumption data in base year (2005) and 2008; technology data of power plants higher than certain scale such as installed capacity, power generation, annual generation hours, power generation efficiency, etc.; historical change of energy consumption by sector and energy type in Guangdong Province; estimated carbon emissions.

2) Technology efficiency data of different types of power generation technologies were collected, analyzed and assessed. As the target of the model is power generation sector, parameters of all present and future possible power generation technologies are required to be provided. Therefore, based on relevant studies and data accumulation in the past by ERI, project team collect plenty of such data, including: technology efficiency of various of power generation technology, power generation costs (investment cost and operation cost), development potential, constraint factors, etc. The applicability of these data on Guangdong Province was also evaluated.

3) Technology efficiency data and economic cost data related to CCS were collected, compared and analyzed. As CCS is on a R&D and pilot phase and there are large discrepancies on the data among pilot CCS projects in different countries, ERI project team compared and analyzed technology efficiency and cost data related to CCS gotten from domestic and foreign studies, and economical and technical parameters of pilot CCS projects in China and other countries. ERI project team also conducted studies on potential CCS cost in Guangdong Province and the relationship between CCS technology cost and other relevant factors. In addition, ERI project team also collected and analyzed cost data of carbon capture, transportation, and storage respectively.
Chapter 6

CCS Capacity Building and Public Awareness

6.1 Partnership CLEAN

In order to achieve the tasks in 4.1, 4.2, 4.5 and 5.1, we have established the first CCS partnership in China: the China Low-carbon Energy Action Network (CLEAN).

Before the GDCCSR project started, stakeholders in Guangdong have limited understanding of CCS technology, and limited industry participation in CCS. No CCS partnership exists in Guangdong province as well as in China.

On 7th September, the network CLEAN was launched in Guangzhou, over 70 people attended the launch meeting. CLEAN provides a communication and cooperation platform for promoting carbon capture and storage readiness in Guangdong and in China. The individual membership is composed of professional researchers from research institutes and universities, economists on energy, decision makers, as well as engineers from relevant industrial bodies covering petroleum, chemical, geology, energy storage and transportation fields. CLEAN also welcome unit members.

So far CLEAN has 52 members from research institutions, industry (electricity, oil, clean energy), finance, NGO, and embassy/consulates.

6.2 Project and partnership websites

Two websites were created as set in task 4.6, one for the GDCCSR project and the other for the CLEAN network. The GDCCSR project website (www.gdccs.org) included the introductions, news, events, and a share panel for GDCCSR project partners to leave messages, upload files and share with each other.

The CLEAN website (www.clean.org.cn) acts as the main website for the partnership which includes CCS news and events in China. This information was updated in time. People can get the information about CLEAN network, such as main work, organization, member management et al. and download the application form in order to participating network activities. Members will get an account id and password, and be able to download shared files.

6.3 Meetings and Workshops

The GDCCSR Launch Meeting

On March 18, the launch of project “Feasibility Analysis of CCS-Readiness in Guangdong (GDCCSR)” was announced in Guangzhou, China. The launch meeting was attended by over 100 participants from government, research institution, industry, Government officials including the director-general of the British department of Energy and Climate Change Caverndish, the ambassador of the British Embassy in Beijing Wood, the vice secretary-general of the Guangdong Provincial Government Yong Chen, the head of the Climate Change department of Chinese National Development and Reform Commision Zhaoli Jiang addressed at the meeting. Chinese academicians Shu Sun and Weidou Ni, leaders of major Chinese CCS projects, and experts from
Chinese, British, Australia, and American institutions and NGOs presented their findings on CCS, and the GDCCSR leader Di Zhou outlined the project. The meeting was reported widely in major newspapers and websites in the province.

The CCS seminar-Summer Assemble

The Guangdong CCS Seminar-Summer Assemble was held on 10 June in Shenzhen, over 50 people from government, industrial and business attended the meeting, including the director of Technology Bureau of Nanshan District in Shenzhen. Information about GDCCSR project, CCS-Ready and situation of CCS in China and UK were presented to the attendees. The attendees were interested in CCS technology and had a heated discussion which focuses on CCS development in Guangdong province in the afternoon round table conference.

The CLEAN network launch meeting

CLEAN network launch meeting was held on 7 September in Guangzhou, over 70 people from government, industrial and business attended the meeting. Information about CLEAN network, CCS in China was presented to the attendees. Representative from Huaneng Group, Shenhua Group and Dongguan Power & Chemical introduced the CCS (IGCC) projects in their company. The attendees were interested in CLEAN network, 36 of them joined CLEAN after meeting.

6.4 Links with government

The project team has been keeping contact with the Department of Energy Conservation and Climate Change of the Guangdong Development and Reform Commission. Before the project launch meeting we visited the department and made a report on the concept of CCS and its possible contribution to Guangdong’s low-carbon development. That was the first time for the department to know the details of CCS. Then, all members of the department attended the project launch meeting. Representative of the department also attended our network launch meeting.

Through this channel, the decision makers in the Guangdong government have become aware of CCS. In the “Action Plan for the Low-carbon Pilot Province of Guangdong” drafted in Oct. 2010, CCS has been included for the first time as a low-carbon technology to be developed. This is a major progress compared with the fact that 8 month ago there was no consideration on CCS at all in drafting the provincial low-carbon roadmap.

6.5 Links with industry

The project team has visited or discussed with industrial companies such as BG(China), CNOOC-Shenzhen, CNOOC-Shell Huizhou, Tianming Power Plant in Dongguan, Foshan power plant, Sanshui Hengyi power plant, Shenzhen Baochang power supply CO, Ltd., et al.. These and other industries have been invited to our meetings and to join our network. Through these activities, many decision-makers have some knowledge of CCS and CCS-ready, most of them were interested in CCS, as well as the CLEAN network. Most significant outcomes are as follows:

1) CNOOC-Shenzhen agreed to support out study of offshore CO2 storage. A meeting was held with their experts, and the structure LF2G1 in the Pearl River Mouth Basin was selected as
our first target Exploration data on the structure have been provided, which made possible our preliminary assessment of this early opportunity for offshore CO₂ storage (See section 2.4 for details).

2) CNOOC Huizhou refinery project phase II was introduced by LinksChina into contact with the British Consulate-General in Guangzhou and the GDCCSR project team. Three parties have an in-depth discussion and came to two conclusions: (1) the high concentration CO₂ produced by their coal-to-hydrogen equipment may be sequestered directly sub-seafloor to the LF2G1 structure offshore; and (2) the power generation facility of the project is suitable for a capture ready design. After the meeting, we drafted a letter to describe the idea, and the letter was sent to the CNOOC headquarters by the Huizhou group and to the UK prime minister by the British Consulate General in Guangzhou.

6.6 Presentations in national and international meetings

The project team includes a number of CCS leading scientists in China and in UK, such as Di Zhou, Xiaochun Li, Qiang Liu, Daiqing Zhao, Jon Gibbins, David Reiner, Xi Liang, and Jia Li. They have attended numerous international, national, and provincial conferences or meetings, presenting their new findings in CCS-related researches. For example, 7 of the project team members have attended the GHGT-10. Among which Di Zhou was financed by the GCCSI.

In particular, Di Zhou was invited or voluntarily to present outlines of the GDCCSR project in various conferences or meetings in Hongkong, Shanghai, Chongqing, Wuhan, Shenzhen, and Zhongshan. A special session “Financing Carbon Capture & Storage” was held Jon Gibbins, Di Zhou, Jia Li, and Xi Liang in the “Climate Change Conference” hosted by the University of Edinburgh, June 11, Hong Kong.
Chapter 7
Future Research Plan

With the firm support of BCG and GCCSI and through the hard works of the GDCCSR team members, the project has progressed as planned in the 8 months of the first year. This has set a solid background and confidence for proceeding to the next two years. Detailed tasks for the next years are presented in the project roadmap. Here we only outline several expected major outcomes:

For the next year:
1) On the emission research, 5-8 major point sources and source-sink matching will be completed in the next year. We expected to have 3 source clusters in Guangdong to cover major emission sources, but it is yet to know if there are enough sink clusters.
2) On the storage research, GIS system will be completed, and effective storage capacity will be calculated for each of the basins. The first opportunity, the LF2G1 structure, will be evaluated for its storage capacity. Seeking for other potential storage sites will be needed to accommodate source clusters.
3) On the cost analysis, cost data suitable for China will be collected, and relevant models will be constructed.
4) On the capture-ready study, capture-ready designs for 1-2 plants will be completed, and the expected cost savings with respect to non-CCR plants will be calculated.
5) On the system modeling, data collection, parameter selection, and system modeling will be completed for most scenarios, some primary conclusions on the carbon-control strategy will be presented.
6) On the capacity building and public awareness, will continue the works of the first year and make our network, websites, and all kinds of links more efficient and more profitable.

For the third year, corporation between sub-projects will be even more pronounced:
1) Emission and storage studies will be completed. Proposals for source-sink cluster matching will be finalized.
2) Carbon-control system modeling will be completed based on the inputs from other sub-projects, including source-sink cluster matching, cost analysis, and CCR analysis.
3) CCS roadmap and policy recommendations for Guangdong will be proposed based on the project findings.
4) Project report will be written, project final meeting will be held, and project outcome will be presented to the government through reports and suggestions, and to the public through national and international conferences, websites, media, and professional papers.