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Options for introducing CO_2 capture and capture readiness for coal fired power plants in China

Jia Li

Supervised by: Prof. Jon Gibbins and Dr. Tim Cockerill

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Department of Mechanical Engineering
Centre of Environmental Policy
Imperial College London

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Abstract

China has been building at least 50GW of new coal-fired power plants every year since 2004. Previous carbon capture and storage (CCS) research has mainly focussed on technology improvements or stakeholder opinion surveys, without picturing the overall concerns and barriers for deploying such technology in China. This thesis therefore explores the engineering and policy requirements to implement CCS and CO_2 Capture Ready (CCR) in Chinese coal-fired power plants, key enablers for future deployment. A preliminary study of the Chinese gasification industry shows there are early opportunities to capture carbon dioxide from gasification plants. However, as power from conventional pulverised coal (PC) accounts for the majority of electricity generated in China, the most promising emission reduction method for China could be through implementation of CCS technology in large PC plants.

An investigation of the current PC plant layouts and operating parameters has been carried out during the course of the study. The results show that, in the absence of CCR designs, a large fraction of such new coal power plants built within the next decade could face 'carbon lock-in'. A site specific system model using ASPEN Plus to demonstrate the possible changes that could be applied to an existing power plant and a retrofit plant is included in the study.

A capture ready power plant site selection method has also been developed, to identify possible sites and to aid understanding of the criteria that should be considered when planning a capture ready plant. A case study of a capture ready power plant in Guangdong province, China shows the benefit of regional planning.

Finally, the result of the first stakeholder perception survey on making new coal-fired plants CCR, conducted in early 2010, are presented and analysed. Evidence for a supportive attitude towards CCR could indicate that this may be a route to early commercial demonstration of CCS in China.

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Nomenclature

BG	Beijing Guolu (Boiler)
BMCR	Boiler Maximum Continuous Rating
CCR	CO_2 Capture Ready
CCS	Carbon Capture and Storage
CEC	China Electricity Council
CO_2	Carbon dioxide
CSLF	Carbon Sequestration Leadership Forum
CV	Calorific Value
DEA	Diethanolamine
DG	Dongfang Guolu (Boiler)
DOE	Department of Energy
ECBM	Enhanced Coal Bed Methane Recovery
EOR	Enhanced Oil Recovery
ESP	Electrostatic Precipitation
FCO	Foreign Commonwealth Office
FGD	Flue Gas Desulphurisation
GHG	Greenhouse Gas
HG	Harbin Guolu (Boiler)

HP	High Pressure
HRSG	Heat Recovery Steam Generator
IEA	International Energy Agency
IEAGHG	International Energy Agency Greenhouse Gas (Programme)
IP	Intermediate Pressure
IPCC	International Panel on Climate Change
LHV	Lower Heating Value
LP	Low Pressure
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
NDRC	National Development and Reform Commission
NETL	National Energy Technology Laboratory
NH_3	Ammonia
NO_2	Nitrous Dioxide
NO_X	Nitrous Oxides
NZEC	Near Zero Emissions Coal Initiative
PC	Pulverised Coal
PRC	People's Republic of China
S	Sulphur
SCR	Selective Catalytic Reduction

SO_x	Sulphur oxide (SO_2 and SO_3)
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USPC	Ultra Supercritical Pulverised Coal

Chapter 1 Introduction

1. 1 Carbon capture and storage

Carbon capture and storage (CCS) has become the focus of considerable scientific research and engineering development in recent years due to its potential for reducing carbon dioxide emissions from fossil fuel plants. According to IPCC (2007), a number of different stabilisation scenarios expect global equivalent CO_2 emissions to be at least half that of the business as usual scenarios (Shown in Figure 1-). This target not only requires measures such as renewable energy, nuclear energy, increased energy efficiency, but also emission reduction from existing fossil fuel infrastructure, such as conventional fossil fuel power plants fitted with CCS (WRI 2008). Developing countries such as China, which has huge coal reserves and a rapidly increasing electricity demand, will need to implement CCS in order to achieve their emissions reduction. Because coal will remain abundant for many years even after oil or gas become scarce (Hawkins et al. 2006), it is not easy to stop using such reserves when they are still available under the ground.

CO_2 Capture and Storage (CCS) technologies, through which CO_2 is captured from stationary sources and injected underground for storage, can reduce carbon emissions from fossil fuel plants by 80-95%. Over the past two decades, CCS has been progressing towards being viable technology for reducing greenhouse gas emissions significantly. Globally, more than 20 large-scale CCS demonstration projects are at the planning stages. According to IEA World Energy Outlook 2009 (IEA 2009), CCS in the power and industrial sectors is likely to represent 10% of total emissions savings by 2030.

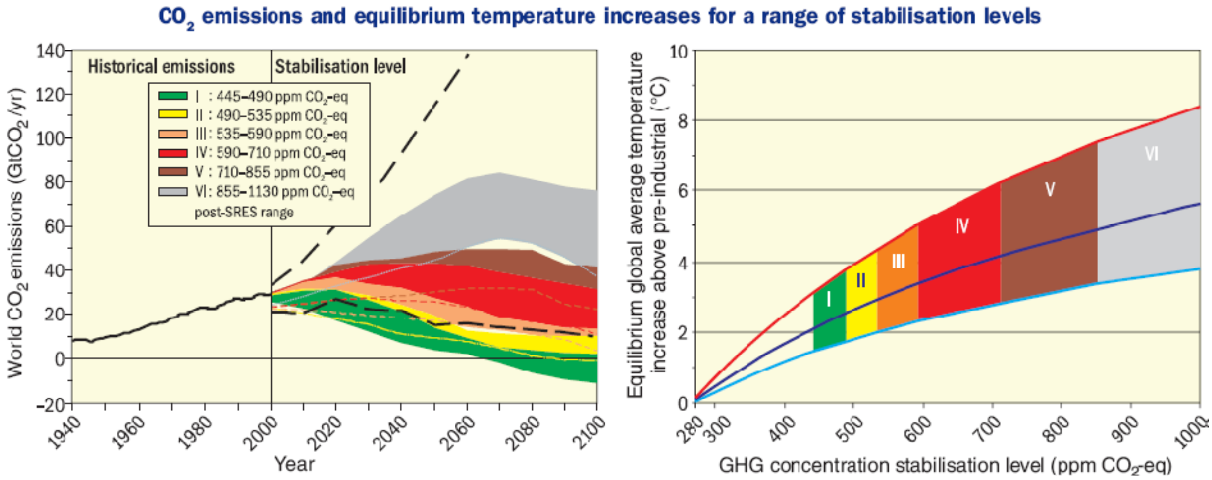

Figure 1-1 Global CO2 emissions for 1940 to 2000 and emissions ranges for categories of stabilisation scenarios from 2000 to 2100 (left-hand panel); and the corresponding relationship between the stabilisation target and the likely equilibrium global average temperature increase above pre-industrial (right-hand panel). *Approaching equilibrium can take several centuries, especially for scenarios with higher levels of stabilisation. Coloured shadings show stabilisation scenarios grouped according to different targets (stabilisation category I to VI). The right-hand panel shows ranges of global average temperature change above pre-industrial, using (i) 'best estimate' climate sensitivity of 3°C (black line in middle of shaded area), (ii) upper bound of likely range of climate sensitivity of 4.5°C (red line at top of shaded area) (iii) lower bound of likely range of climate sensitivity of 2°C (blue line at bottom of shaded area). Black dashed lines in the left panel give the emissions range of recent baseline scenarios published since the SRES (2000). Emissions ranges of the stabilisation scenarios comprise CO2-only and multigas scenarios and correspond to the 10th to 90th percentile of the full scenario distribution. Note: CO2 emissions in most models do not include emissions from decay of above ground biomass that remains after logging and deforestation, and from peat fires and drained peat soils.* Quoted from(IPCC 2007).

As most major economies (incl. UK, France, China, Japan and other countries that signed the Kyoto Protocol) have already committed to controlling greenhouse gas emissions (UNFCCC 2010), ideally, all new thermal power plants, oil refinery plants, cement kilns, and steel plants should not be permitted unless they are built with full scale CCS facilities. However, deploying CCS widely at a large scale is currently facing two major challenges: a lack of experience in building and operating commercial scale integrated CCS projects and insufficient financial incentives to provide a fair return for investors (i.e. the relatively low cost of a carbon emissions permits (or allowances) versus high abatement costs for CCS implementation)(IPCC 2005). Before these challenges are addressed, new fossil fuel utilisation plants in the next decade should be designed and built to be Carbon Capture Ready (CCR) status to ease retrofitting of CCS in the future (IEA GHG 2007)

1.1.1 Status of CCS technologies

The capture process is classified into four categories: post-combustion, pre-combustion, oxyfuel and separation from industrial processes (IPCC 2005). Examples of most of CO_2 separation technologies are mature and in commercial use, except for oxyfuel which is still in the pilot demonstration phase. However, more research and demonstration is required to reduce the energy penalty, the costs of the capture process and to produce viable 'second generation' reference plants that are suitable for widespread replication (IPCC 2005).

CO_2 captured from stationary emissions sources will be transported to storage sites. Pipelines are considered one of the most economic ways to transport mass amounts of CO_2 (IPCC 2005). The construction and operation of a long distance CO_2 pipeline has been commercially available for more than 30 years. There are more than 6000 km of CO_2 pipelines in North America (Morgan 2008).

CO_2 can be injected into deep geological formations (below 800 metres) for storage. The oil and gas industry has experience of injecting a large quantity of CO_2 into saline formations, oil and gas fields. The CO_2 injection technology is mature. CO_2 Storage in unminable coal beds requires further demonstration (IPCC 2005). Ocean sediment storage is another option, which has a much greater potential capacity, but it is currently only at the research stage. In summary, most of the components in CCS technologies are mature and commercially available (IPCC 2005). The priorities in CCS development are cost reduction and demonstrating an integrated CCS system (Liang et al 2009).

1.1.2 CCS demonstration projects

The real bottleneck in CCS deployment is the lack of suitable demonstration projects and the scale of projects generally. According to the Stern Review (2006), capturing CO_2 from fossil-fuel power stations is likely to be essential to deliver steep cuts in emissions. Some stakeholders are concerned that CCS technologies have not been proven because of a lack of industrial projects. In fact these concerns are unfounded. More than 100 industrial CCS projects are in place globally and about 20% of these are currently in operation (Captureready 2009). However, the scales of all the demonstration projects are far too small. A 500MW plants produce 3 MtCO2/yr (Koomey et al 2009). However, the biggest CCS project from power plants only captures 120ktCO_2/yr, and does not have storage built as an integrated project (MIT 2010). Other capture projects include the Vattenfall 30MW Schwarz Pumpe pilot plant in Germany, Chongqing Shuanghua 100ktCO_2/yr project. A few storage projects use CO_2 from natural gas, such as the Sleipner 1MtCO_2/yr storage project in Norway which has been operated for over 10 years, the Total Lacq 75,000 tonnes/yr CCS pilot in France. Other storage projects use CO_2 from industry gas such as, the North Dakota-Weyburn 1.5MT tonnes/yr (CSLF 2009).

Europe aims to have up to 12 demonstration projects by 2015 and is preparing a knowledge-sharing framework of CCS projects, though some experts question the slipping timetable (EU 2007). Steven Chu has suggested a more ambitious target: the US could have 5 to 10 CCS commercial demonstration projects operational by 2016, and ready for wider commercial deployment by 2019 (Senate 2010). Although the Chinese government has not yet supported CCS demonstration projects assertively, large state-owned energy companies such as Huaneng Group, Chongqing Yuanda

Environment in China Power Investment, GreenGen and Shenhua have proposed or developed a number of pilot scale CCS projects (for details of projects see He (2009))

A number of bilateral or multilateral initiatives and partnerships have been established in order to accelerate risk/funding/knowledge sharing, technology transfer, or capacity building, such as the Carbon Sequestration Leadership Forum (CSLF 2010), FutureGen alliance (2010), the UK-EU-China Near Zero Emissions Coal Initiative (NZEC 2010), the US-China Clean Energy Research Centre (Whitehouse, 2009) and the Australian government is providing the Global Carbon Capture and Storage Institute (GCCSI 2010) with a 100 million Australian dollars per year to support global CCS demonstration projects.

1.2 Carbon capture ready (or 'CCS ready') and retrofitting potential

Before CCS is technically and economically viable, a large number of fossil power stations will still be built and emit CO_2 to the atmosphere. According to estimates by the IEA (2009), China and India alone may build thermal plants producing more than 400GW of power in the next decade. Modifications to make new plants CO_2 Capture Ready (or 'CCS Ready') are important to minimise the risks of future 'carbon lock-in' and ease retrofitting of CCS. "*Developers of CCS ready plants should take responsibility for ensuring that all known factors under their control that would prevent installation and operation of CO_2 capture have been identified and eliminated, including* (IEA GHG 2007; quoted from Liang et al 2009) :

- *A study of options for CO_2 captures retrofit and potential pre-investments*
- *Inclusion of sufficient space and access for the additional facilities*
- *Identification of reasonable route(s) to store CO_2"*

Modest CCR investment is less than 1% of original fixed capital expense, according to an estimate by the IEAGHG (2007). However, it could reduce the possibility of early closure by 7 to 10% and increase its retrofitting possibility by 5 to 7% (Liang et al 2009). This was also the conclusion of a recent study by the UK-China Chinese Advanced Power Plants Carbon Capture Option (CAPPCCO) project in 2009. Nearly half of existing non-CCR Chinese coal-fired power plants would not be able to be retrofitted based on a survey of 143 power plants in China in the CAPPCCO project (see chapter 4).

1.3 Research aims

The overall research question of "How carbon capture and storage might be introduced for coal-fired power plants in China?" is broken down into a series of sub-topics:

- Gasification options – will gasification technologies help to accelerate CCS or capture ready in China?
- Retrofit of capture to existing plants – can existing power plants, particularly large sites easily be retrofitted in the future? If yes, what is the percentage of plants that can be easily retrofitted? How can those plants be retrofitted?
- Making new power plants capture ready – how feasible might it be to have new Chinese power plants built capture ready so that barriers to future capture retrofit will be less? What should be the strategy to make capture ready happen in China?

Although this thesis covers these areas in some detail the size of the Chinese coal power industry means that it can only be a starting point for such an analysis. It does, however, provide a basis for continued work in the area by establishing a number of key tools for assessing and facilitating the introduction of CCS in China:

a) identifying different types of capture ready options appropriate to China, pre-combustion and post-combustion

b) a comprehensive database of large size plants and their suitability for capture retrofit

c) creating easy to use capture simulation models

d) changing the current site selection process to include capture ready,

e) suggesting regional planning include capture ready to accelerate the development

f) consulting engineers on hurdles for introducing capture ready in China.

Not only technical but also economic and social aspects of these issues have been examined. Most of the methodologies applied or developed during the study can be updated and extended in the future, for example the power plant site assessment and the survey for assessing the perception of capture ready by engineers and policy makers. Further work in all areas will be required to allow for the rapid evolution of the Chinese power industry and the development of CCS technologies, and thus this thesis constitutes a foundation for future studies in this field.

1.4 Thesis outline

Chapter 1 describes the carbon capture and storage technology in general and outlines why capture ready is essential in China. The research aim and thesis outline are also covered in this chapter.

Chapter 2 summarises the current gasification technology implemented in China and appraises the existing literature on capture ready for pre-combustion plants. One model that has been widely suggested to address coal-based CO_2 emissions in China was for existing power plants in China to be replaced by technology involving gasification, since China is quite proficient at building gasifiers ((Williams 2003), the series of Harvard IGCC workshops (2007). However, it has become clear during the course of the thesis that existing pulverised coal (PC) plants will continue to produce electricity for the next 20 -30 years and new PC plants are still being built and planned. The gasification potential for CCS is not sufficient in China and this technology hurdle has provided technical and economic uncertainty for capture ready gasification plants as a route to CCS in China.

Therefore, the follow-on study focuses on the potential for future implementation of CO_2 capture in PC plants in China. Three complementary surveys are carried out in order to examine and address the following points:

- Scope for capture retrofit at existing power plants
- Capture ready for future power plants based on existing infrastructure
- Stakeholders' perceptions of power plants being built in a capture ready state

Chapter 3 presents an overview of the current Chinese electricity industry and estimates its potential development through literature reviews. Most of the electricity generated in China is from PC plants and these are forecasted to keep on providing the dominant contributions in the future years. The prediction of larger, higher efficiency PC plants being produced and installed in China is made based on the current national policy of energy saving and increased efficiency. The policy of replacing smaller size units with larger size units is also discussed and the impact of the policy on future electricity market development is analysed.

Chapter 4 reviews the layout and surrounding geographic information of over 134 existing power plants with over 1GW installed capacity in China. The plants have been grouped in two main categories and three sub categories based on their surrounding environments. Furthermore, the retrofitting potential for these plants has been estimated based on the space of the sites, access to storage places, plant size. Published retrofit studies on existing sites are described in the thesis, with individual site analysis. The hurdles for retrofitting existing power plants are also discussed.

Chapter 5 considers site-specific parameters for retrofitting PC plants. The 1000MW power plant in Zhouxian is used for ASPEN Plus simulation modelling as an easy example for power plant operators or plant owners to understand the principal differences between a conventional PC plant and a carbon retrofitted plant. The method of creating such a model has been laid out in detail for plant operators as the trial version of a retrofit simulation tool. Finally, a list showing possible additional equipment and their operating parameters is summarised for cost and space estimation.

Chapter 6 introduces a methodology for power plant site selection for capture ready. The assessment table is presented as a checklist in the planning stages. A spider chart is created to use when more than one site is available as a possible candidate site for capture ready plants. New suggestions are given with an aim to inform the decision-making process when deciding on a capture ready plant. When these are applied in real case scenarios, the decision making process could be significantly optimised. A regional planning concept is proposed in order to overcome the economic development imbalance in China.

Chapter 7 presents the results of a survey of power plant engineers undertaken in order to understand the engineering and economic drivers and barriers to implementing CO_2 capture ready design concepts on newly built coal-fired power plants in China.

Finally, conclusions are presented and suggestions for future work are provided.

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Chapter 2 Carbon Capture Ready and Capture Readiness for Gasification Plants in China

This chapter is written based on Jia Li's transfer report in 2008 (Li 2008) and a paper for the 7th European IGCC Conference in 2006 (Gibbins, Li et al 2006)

2.1 Chinese gasification industry overview

A qualitative assessment of the early opportunities for capturing carbon dioxide from advanced gasification plants, and of design guidelines for carbon capture ready gasification plants, is made based on current gasification development in China. The assessment first illustrates the development of different types of gasification technology in China. A technical analysis of the performance of the different gasifiers is conducted based on the key factors that will affect the performance. Most of the less advanced gasifiers are used to produce ammonia, urea and hydrogen on a small scale (Xu 2005). Capturing carbon dioxide from high concentration stationary emission points could be seen as an early opportunity for carbon capture demonstration. Carbon capture ready in those plants could be as simple as reserving enough space for a compression and CO_2 conditioning unit. However, given that the total amount of emissions and the scale of emission sources are relatively small at those plants, the potential emission reduction is very limited.

During the past decade, large size entrained-flow gasifiers introduced into large scale coal to liquid (CTL) or coal to chemical (CTC) plants consumed around 2000 tonnes of coal per day per gasifier. Greenhouse gas emissions from these plants are much bigger than from plants with smaller scale gasifiers. A number of those plants using advance entrained-flow gasifiers are in the process of applying for expansion as well (GCC 2007). Hence, applying carbon capture technology, especially making those plants carbon capture ready, could have a significant impact on emission reductions in the future. Although there is no Integrated Gasification Combined Cycle (IGCC) power plant in operation in China at the moment, the Greengen IGCC plant in Tianjing has started construction (ChinaFAQ 2010). Capture ready for those plants is also important to avoid carbon lock in.

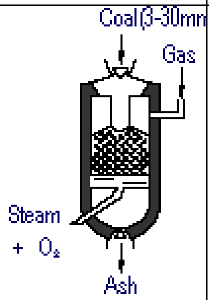
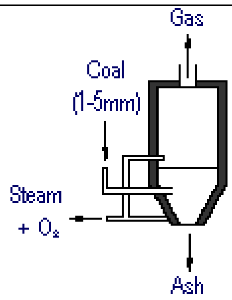
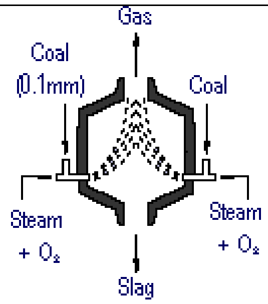
2.1.1 Introduction of gasifier

The additional cost of carbon capture in gasification process systems was projected to be significantly lower than the cost of capture from pulverised coal (PC) plants (Meng et al. 2007; NZEC 2009). Gasification was also considered as one of the most important coal transformation technologies for China (Chen and Xu 2010). Since China has the largest number of gasifiers around the world, it could be practical and economical to start capturing carbon dioxide from some of the gasification plants in the near future, such as ammonia, urea and hydrogen plant. This does not necessarily mean capturing CO_2 immediately, but planning the plants so that they could be easily and economically retrofitted into a carbon capture plants later on, or even be used as an early opportunity for a carbon capture and storage (CCS) demonstration project. Capture ready design could be as simple as leaving sufficient space for additional shift, capture and compression units and having undertaken a feasibility study to ensure a retrofit can be undertaken readily. However, it is widely recommended that new IGCC plants should be built with carbon capture rather than being only carbon capture ready (Rutkwoski, et al. 2003), because from a technical point of view it is hard to match the gasifier output and the turbine capacity both before or after capture retrofit. Economically, capture ready cannot demonstrate a great saving in the overall IGCC capital investment. The research presented in this chapter therefore focuses on capture ready from chemical processing plants that use gasifiers for generating syngas in China. The following sections present the background information regarding types of gasifiers, a China gasification industry overview and a roadmap for deploying carbon capture ready design in gasification plants.

Generally, gasifiers can be grouped into three types: fixed-bed, fluidised-bed and entrained-flow; for a detailed discussion of gasification technologies see (Higman and Burgt 2003). In a recent survey Xu (2005), from the Coal Research Institute in China, estimated that there were more than 8000 gasifiers in operation in China. Most of those were, however, atmospheric pressure fixed-bed gasifiers based on obsolete designs (principally UGI – United Gas Improvement Company) and with low coal capacities (less than 100 tonnes/day) and high levels of environmental pollution (Xu 2005).

Table 2-1 shows a comparison of more modern gasifiers used in China. Apart from entrained flow gasifiers these include pressurised fixed bed gasifiers (Lurgi Mk IV) of which there are currently 7 in operation in China (Turna 2007). The coal consumption rate is 54 tonne/day (Dyk et al. 2006). The first 5 Lurgi units were installed in 1987 at Tianji Coal Chemical Company in Lucheng, which produced 300kt of ammonia, 500kt of HNO_3, 900kt of nitro phosphate and 200 kt of ammonium nitrate (explosive grade) every year (Tianji 2007). In 2000, another 2 dry ash Lurgi gasifiers were built in Yima Coal Gasification Plant producing 80Mton of methanol every year. A limited number of fluidised bed gasifiers are also in use, including 2 new-build U-GAS gasifiers in Shandong province for methanol production installed in 2009 (8 of the earlier U-Gas gasifiers installed at Shanghai Coke and Chemical plant are apparently abandoned) (Huang 2002). The world's first transport gasifier –KBR gasifier- will start operation in 2011 at Dongguan in China in an IGCC plant (KBR 2009). This plant is also potentially the world's biggest IGCC site at 1.6GW. A fluidised bed gasifier invented by the Institute of Coal Chemical (ICC) in China has recently moved to industrial plant scale, and can handle 300 tonnes of coal per day (ICC 2007).

Table 2-1 Comparison of Gasifiers used in China (Updated 2009Dec base on Li (2008))

	Fixed-bed		Fluidised –bed			Entrained-flow				
Simplified Models of Gasifier										
Maker	Lurgi MkIV[1]		HTW IGG	CFB U-Gas	TG KBR	GE	SHELL	SIEM-ENS	MBON	TPRI
Gasifiers[2]	7		6(1)	10	1	19	28+9	5	2	(1)
Tars Control	Very high Easy		Intermediate Intermediate			Absent Very complex				
Scale	< 20 MW_t		10< MW_t < 100			> 100 MW_t				
Feedstock Size Type	Very critical 3 – 30mm Anthracite, coke		Less critical 6 – 10 mm Low rank coal has the best performance, such as lignite			Very fine particles <0.1mm Low ash coal				
Coal demand	Small, normally up to 100t/d		Medium, Between 100-1000t/d			Big, Over 1000t/d				
Oxidant demand	Low		Moderate			High				
Steam demand	High		Moderate			Low				
Outlet gas T (^0C)	425 – 650 [3]		950 – 1100 for coal[4] 800 – 950 for biomass			900 - 1600				
Operating T (^0C)	Around 1000					1500	1500	1400-1700		
Operating P (bar)	Atm	25-30	25			30-70	40	40		60

[1] Only Lurgi MkIV is discussed in this table, another widely used UGI gasifier is discussed in other section.

[2] The number shown for Entrained-flow gasifiers is the number of plants in China , not the number of gasifiers. The cut out data is end of 2009.

[3] Or higher than coal agglomeration T

[4] Below ash softing point for coal, except IGG, which need to be between ash softing and melting point, and T is 1050-1100

The bulk of the modern coal gasifiers in use in China are, however, entrained-flow designs, mostly licensed from foreign suppliers (GE, Shell, Siemens) but now an increasing number of Chinese designs (MBON, TPRI, ICC) are also available. These are used in chemical plants, coal to liquid plants and latterly in Integrated Gasifier Combined Cycle plants (IGCC). There are also a limited number of similar liquid fuel gasifiers in use in refineries in China (NETL 2009).

In this chapter, only plants using the older fixed-bed coal gasifiers, because of their very large numbers and widespread distribution, and entrained coal flow gasifiers, because of their scale, will be considered for carbon capture and storage in subsequent sections. The liquid gasifiers will not be discussed because few new ones are currently being built.

2.2 Potential CCS applications for low-technology fixed-bed gasifiers

2.2.1. Fixed-bed gasifier technology and application

Fixed-bed gasifiers are also called moving-bed gasifiers. Coal or coke is fed from the top of the gasifier and oxidant is injected from the bottom. Compared with the gas's upward velocity, the coal's downward velocity is very slow. Therefore, the coal can be treated as stationary for most purposes, hence its name: fixed-bed gasifier. In actuality, the coal (and later char and ash) moves downwards at a slow speed, which is why it is also called a moving-bed gasifier. This type of gasifier usually has a rotating coal distributor at the top of a cylindrical reaction vessel and a rotating grate at the bottom of the reactor.[5] The coal consumption of the gasifier is normally under 100tonne/day and the operating pressure and temperature is the lowest of all the other types of gasifier. The most common type of fixed-bed gasifier in China is the

[5] BGL slagger – dry bottom Lurgi top plus slagging bottom Turna, O. (2007). Sasol-Lurgi fixed bed dry bottom gasification for fuels and chemicals. 2nd International Freigberg Conference on IGCC & XtL Technologies, Freigberg, Germany.

United Gas Improvement (UGI) gasifier. It can be operated either continuously or intermittently. The manufacturing of the UGI gasifier is also much easier than other advanced gasifiers. Xu (2005) states that there are more than 3000 UGI gasifiers running in around 900 small scale fertilizer plants all over China. Liu (2007) also states that there are around 400 large UGI gasifiers (diameter 2740, diameter 3000 meters) used in medium size fertilizer plants and another 5000 fixed-bed gasifiers (diameter2400 to 2600 metres) used in smaller scale fertilizer plants. However, a detailed distribution of the gasifiers, the quality of the carbon dioxide and its end use are unknown due to a lack of available data. (See Figure 2-1 for ammonia and hydrogen production process) Only recently have some regional surveys taken place to examine the carbon dioxide sources in China (Captureready 2010).

As mentioned above, the UGI gasifier can be operated either continuously or intermittently. In a continuous process, oxygen, or oxygen enriched air, is used as oxidant. For the intermittent process, air and steam are used alternately. Most of the UGI gasifiers used in China are the intermittent type. The UGI gasifier also has a water wall built outside the reactor for steam generation. Around three quarters of the ammonia produced in China is based on the intermittent gasification process, which means it has a lower carbon dioxide emission rate than the continuous process. The 32 million tonne/y of ammonia produced through the intermittent process together with the 48 million tonne/y of nitrogenous fertilizer has a slightly higher cost for capturing the carbon dioxide (Li 2008), but it is still relatively cheap in terms of additional investment into the plant. Chen has calculated that the emission factor for an ammonia plant is 4.21t CO_2/t ammonia based on the case of Hebei province. The average emission factor for an ammonia plant is 3.8 t CO_2/t ammonia (IFA 2009). Based on their results, the carbon dioxide emission from ammonia plants will be between 121.6 to 134 million tonne CO_2/y in China.

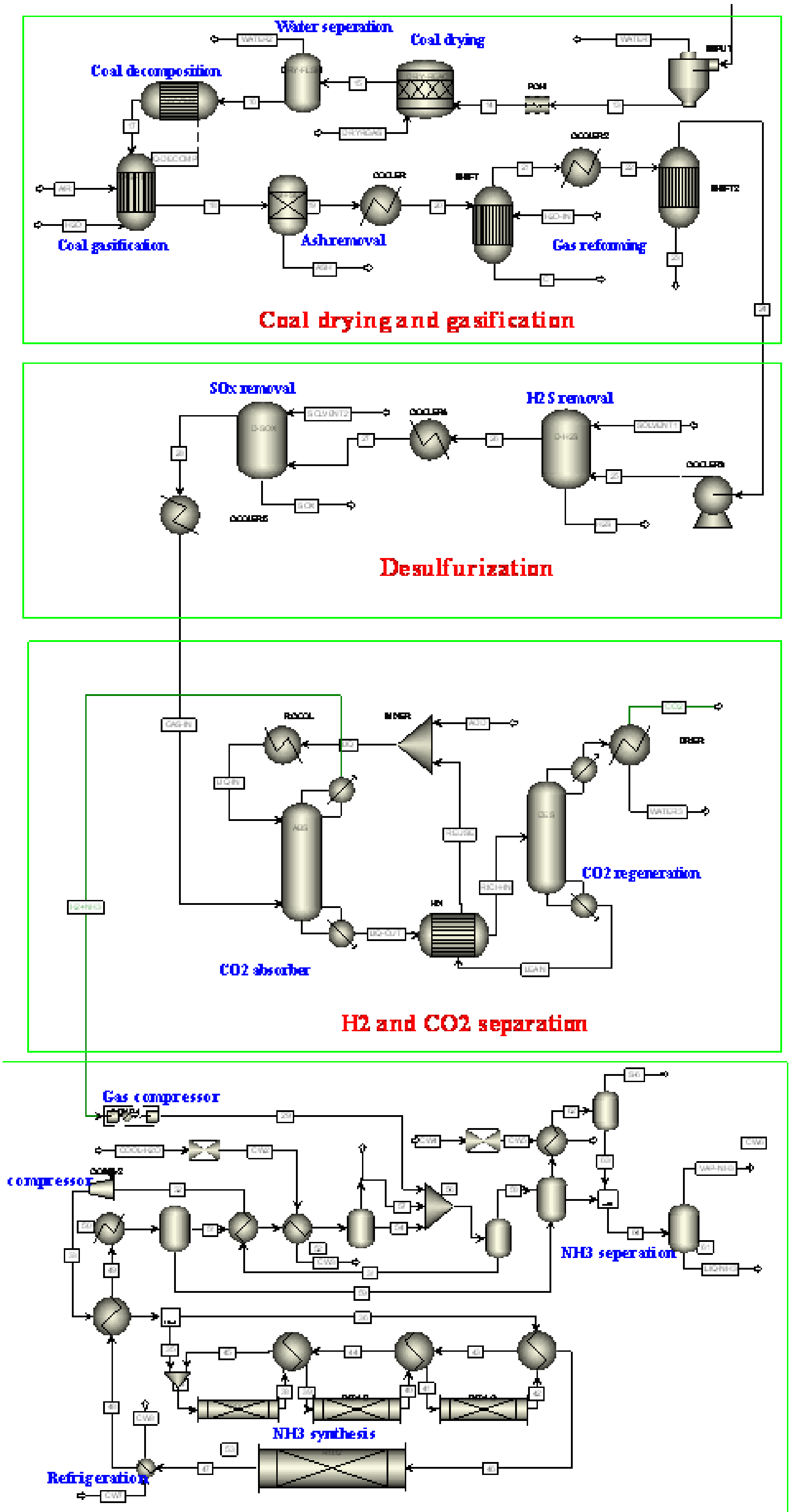


Figure 2-1 PFD of hydrogen and ammonia production

Another more advanced fixed-bed gasifier is the Lurgi MkIV gasifier. Although it does not have such a wider application as the UGI gasifier, it is one of the most advanced gasifiers of its type. Because of its wide application in the CTL industry in South Africa, suggestions have been made to conduct more serious study on this type of technology (SASOL 2006).

2.2.2 Possible CCS applications for fixed-bed gasifiers

This section considers fixed-bed gasifiers as an option for carbon capture and storage in China. The concentration of carbon dioxide and inert gases (mainly nitrogen) that are produced through specific fixed bed gasification process is an essential factor in determining the feasibility of CO_2 capture. The data in Table 2-2 shows operational and computational results for different gasifiers. The carbon dioxide concentration from intermittent and continuous UGI gasifiers is 8.3% and 13.5% in the process gases and the nitrogen in the processed gas is also more than 10%. The air blown technology will cause difficulties when separating the carbon dioxide from the nitrogen later on. Hence, when justifying the retrofitting of fixed-bed gasification plants for carbon capture, the oxidant need to be considered as one of the important criteria.

Table 2-2 Performance of different gasifiers (Liu 2007)

Gasifier	CO	H_2	CO_2	CH_4	N_2+Ar	O_2	H_2S +COS
UGI(Intermittent)	42.6	38.6	8.3	0.2	10.2	0.1	
UGI(Continuous)	42.5	29.7	13.5	0.4	13.7	0.2	
Texaco	42.5	35.34	21.52	0.01	0.48	0.01	0.14
Two stage	67	1.1	29	0.4	2.1	0.4	
GSP*	60.63	23.59	4.95	0.01	10.67	0.04	0.11
Unit: mole %; *: Simulation result for GSP gasifier							

Carbon capture ready design for gasification plants with a high concentration of carbon dioxide should be considered as the easiest and most economic plan when preparing to capture greenhouse gases in the future. Most of the plants are operating with fixed-bed gasifiers or fluidised-bed gasifiers. The total amount of coal consumption is low for a gasifier and the gas output that is needed for further processing is small. CO_2 capture technologies for plants of this scale are mature and have been applied around the globe. Figure 2-2 shows a process flow diagram (PFD) of how carbon capture units could be added to a typical hydrogen and ammonia plant. The syngas produced after gasification is sent to a shift reactor for water gas reaction, where the carbon monoxide and steam is reacted and turned into carbon dioxide and hydrogen. In a non-capture plant, the carbon dioxide is vented into the atmosphere after separation with hydrogen. In order to store the carbon dioxide only simple compression and a temporary storage unit needs to be added to the plant. Hydrogen production plant should be considered the easiest option for retrofit when carbon capture is required by regulation. Currently, only three chemical plants in China are capturing carbon dioxide at over 30,000 tonne/year capacity. The Chinese hydrogen production capacity is around 10 million tonnes per year, making China one of the world's biggest hydrogen production countries (Li et al. 2007). Most of the carbon dioxide by-product is vented into the atmosphere either because the demand for carbon dioxide is relatively small or because the plant operator cannot find a guaranteed market for it. This means that around 220 million tonnes of carbon dioxide emissions could be captured relatively cheaply with the cost of compression. But even the largest hydrogen plant located in Edors, Inner Mongolia, only contributes 1.8% of the total production in China; most of the other hydrogen plants are on a much smaller scale than the chemical plants (Li et al. 2010). Other chemical plants producing hydrogen were built along the south east coastal area or within the traditional refinery production area in the west using less advanced gasification technology. The widespread geographical distribution of hydrogen has created a unique experimental environment for developing CCS in the future. There is the possibility that the carbon dioxide could be used to test local saline aquifer storage capacity and physical property, and to provide data for long-term storage prospect; the storage capacity for different areas could be estimated more precisely by this method.

The hydrogen production process is similar to ammonia production before hydrogen is reacted with nitrogen. In an ammonia plant, hydrogen will react with nitrogen to form NH_3. For small-scale plants, the major difference is that during the coal gasification process, air and steam react with coal instead of oxygen in an ammonia plant. It is difficult to separate the resultant gas, which contains nitrogen, from carbon dioxide. Yet in the ammonia production process, nitrogen is needed to react with hydrogen to form NH_3, and thus the mixed gas can be used as reactants in later processes. Therefore, smaller ammonia plants tend to avoid investing in air separation units and instead use air as the feedstock. In this case, capturing the carbon dioxide is much more difficult and the process is similar to capturing carbon dioxide from conventional pulverised coal (PC) plants, but with a higher carbon dioxide concentration. When air is used as the feedstock, the ammonia plants using gasification technology should not be considered as a cheap option at this stage. However, if the plant has the potential to be retrofitted into oxygen feed plant, it would be possible to share the same capture method as a hydrogen plant. At the same time, capturing carbon dioxide at individual small-scale ammonia plants creates problems when collecting the carbon dioxide for storage since the pipeline infrastructure needs to connect several different points, which might affect the total cost of carbon capture. Therefore, a source and sink matching study is essential when deciding which plant is suitable for carbon capture.

Carbon capture in a urea plant is similar to that in ammonia and hydrogen plants, except that the amount of carbon dioxide left for storage is less. Figure 2-2 shows the PFD of the urea production after NH_3 is produced. Carbon dioxide is used as one of the raw materials to produce urea; therefore, the amount of carbon dioxide left for capture is down by a third from oxygen fed gasifier. For the air fed gasifier, carbon dioxide concentrations are very low, making it unsuitable for retrofitting.

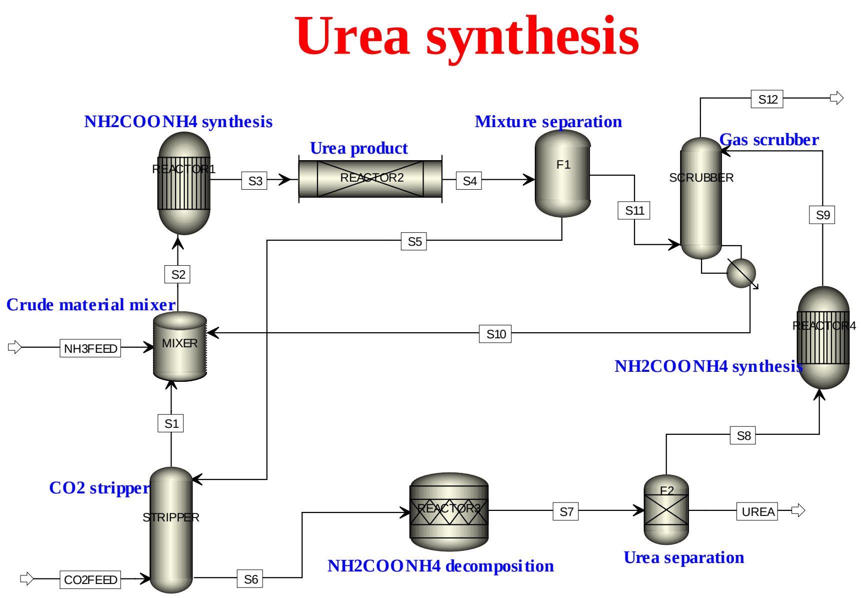


Figure 2-2 PFD of Urea production (XLX 2010)

Meng et al (2007) summarises the early opportunities for storing highly concentrated carbon dioxide from chemical plants by source and sink matching. The study also gives a comprehensive list (up to 2007) of modern gasification plants which produce hydrogen, urea or dry ice as one of the secondary products. All the plants it studied have a stream of highly concentrated carbon dioxide vented into the atmosphere. However, at the time the study was conducted, more than half of the gasification plants were still under construction and were not considered suitable for early demonstration. The storage option for Meng's study was based on an economic transport distance to oil or gas fields being up to 150km. If carbon dioxide becomes mandatory in the future, the distance to a storage site could be extended because of the upfront saving in carbon dioxide separation costs.

2.3 Potential CCS from applications using entrained-flow gasifiers

2.3.1 Advanced fluidised bed and entrained flow-gasifier technology

When gas velocity is high enough to support the solid against gravity in the bed, the solid can move like liquid and form several layers. If the gas speed is accelerated further, the gas will form bubbles under the solid layer. When bubbles rise, the solid layer will break, similar to the air escaping from boiling water. Fluidised-bed gasifiers are designed based on the above principles.

Fluidised-bed gasifiers in China are mainly used for generating industrial fuel gas, and only a few are used for ammonia production (Men 2005). Coal is grounded to 6-10mm particle size, which is light enough to be lifted up by the upward gas flow, but not too fine to be blown out of the gasifier. More than 95% of the solids content in the gasifier is ash; only a small portion is coal or biomass (Higman and Burgt 2003). In order to prevent the ash agglomerating inside the reactor and forming larger particles, fluidised-bed gasifiers are normally operated below the ash softening point, except for the U-Gas agglomerating fluidised bed. (For the U-Gas gasifier, coal will stay in the gasifier for 45-60 mins, but the operating performance is not stable.) This limits the operation temperature in the range of 950^{o}C –1100^{o}C for coal and 800^{o}C –950^{o}C for biomass. However, the low temperature also results in more tar in the outlet gas, since less thermal cracking of tar will happen if the temperature is not high enough. Therefore, the product syngas is more suitable for industry fuel gas than raw gas for ammonia or fertilizer plants.

Low rank coal such as lignite, peat, or biomass is suitable for fluidised-bed gasifiers because of their high reactivity at low temperature and lack of caking properties. The size of the feed will affect the process significantly. If the coal particles are too fine, the solid layer might not break before it gets close to the exit and might block the system; if they are too large, they might be too heavy for the fluidising gas to lift up. Therefore, the bubbling fluidised-bed needs to be monitored constantly (Higman and Burgt 2003).

Oxygen and steam are often used as the oxidant. The oxygen consumption of fluidised-bed gasifiers is higher than fixed-bed gasifiers and lower than entrained-flow gasifiers. The fluidised-bed gasifiers can provide excellent conditions for heat and mass transfer inside the reactor. However, their carbon conversion ratio is lower than other types of gasifier, as particles have different residence times in the gasifier. As a result, the highest conversion rates for fluidised-bed gasifiers typically only reach 97% even with low-rank coals (Higman and Burgt 2003).

The agglomerating melting ash fluidised-bed gasifier has been successfully implemented in China, following some failures with imported designs (ICC 2007). Dry coal at a size smaller than 6mm is used as fuel, while air and oxygen are used as blast. Coal and oxidant are continually injected into the gasifier from the bottom. The operating temperature is between 1050 ^{o}C and 1100^{o}C. The un-reacted coal and ash coming out from the top of the gasifier is collected by two cyclones and sent back to the gasifier to enhance coal conversion and reduce phosphor contents in the ash. The syngas contains almost no tar and hydroxybenzene, which make it easy to clean.

The ash collecting system is also relatively simple. The key technique for agglomerating fluidised-bed gasifiers is to control the softening point of the coal. If the temperature at the air/oxygen injection level reaches the fuel's softening point, the coal will begin to fuse. As the lump of agglomerated ash grows, it becomes too heavy to remain in the bed and falls to the bottom. When the agglomerated ash drops out, less ash remains in the gasifier. Therefore, the carbon conversion rate can be higher than in other fluidised-bed gasifiers. The restriction for the agglomerating fluidised-bed gasifiers is that the gasifier needs to be operated between the ash softening point and the ash melting point. Usually, oxygen or air is injected as the fluidising gas to provide an agglomerating environment (ICC 2007).

Entrained-flow gasification technology can be used in producing syngas, fuel and generating electricity. The technology has been recommended as a replacement for the intermittent fixed-bed gasifiers in small to medium scale nitrogenous fertilizer plants. In order to save costs, it can also use soft coal instead of anthracite in synthesis ammonia production. This means that the plant owner will have a wider choice of coal for feeding into the gasifier, and therefore can select the coal locally and reduce the transportation costs for better ranking coal elsewhere. In an entrained-flow gasifier, fine coal particles (<100μm), either dry or in a slurry form, are reacted with steam and oxygen at high temperatures (~ 1600ºC) and elevated high pressures (40 bar to 70 bar). Coal conversion rates are high, for example, the current operating Shell gasifier has a throughput of 1000 - 2250 tonnes/day; a GE gasifier has a throughput of 350 - 2200 tonnes/day; and the throughput of a Siemens gasifier is normally 2000 tonnes/day (NETL 2009).

GE, Shell and Siemens are the main technology providers for installed Chinese entrained-flow gasifiers. Chinese entrained-flow gasifier technology is being developed by the Thermal Power Research Institute (TPRI) in Xian, Shan'xi, and East China University of Science and Technology (ECUST) has also invented the two-stage gasifier and the Multi-Burner Opposed Nozzle (MBON) gasifier (Li 2008).

Both Shell and GE started their gasifier businesses during the 1980s by providing residue oil gasifiers for visbreakers[6] in China. 12 of these plants are still running (Li

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[6] A processing unit in oil refinery which aims to produce more expensive products and reduce the amount of heavy residue produced.

2009a). But with oil prices running high in recent years, building refinery gasifiers which use residue oil are not an economic investment any more. While the oil price has increased more than coal price in recent years the final products for both feedstocks are sold at a similar price in most areas. Therefore this chapter will not cover this technology. There are currently 19 coal slurry gasification plants using GE gasifiers, 18 Shell dry coal gasification plants in operation and 9 in construction, and another 2 Siemens large scale CTL plants (Li 2009a; NETL 2009; Siemens 2009). GE started to sell coal gasifiers in 1993, while Shell started to build gasifiers in 2006. On average, Shell and Siemens have been providing gasifiers with a coal consumption rate of 2000t/d in recent years (Li 2009a).

2.3.2 Entrained-flow gasifiers in chemical applications already producing concentrated CO_2 streams

Most of the large-scale entrained flow gasifier plants produce methanol, dimethyl ether (DME) as transportation fuel or feedstock for the production of other chemicals with entrained-flow gasifiers. Because oxygen is used as feedstock instead of air, highly concentrated hydrogen is produced during the process. Therefore, carbon dioxide could be captured at the cost of adding a compression and storage unit on site. The treatment afterwards is similar to that used in fixed-bed gasifiers, using oxygen as feedstock.

2.3.3 Entrained-flow gasifiers in large-scale coal to liquid (CTL) plants

The Shenhua[7] direct liquidation plant in Erdos produces 4.16 million tonnes of carbon dioxide each year, of which 70% has a carbon dioxide concentration of over 90% (Daily 2009). Carbon capture ready for these plants can be as easy as reserving space for the compression unit and storage/transport units when new plants are built. The economically-viable distance to storage sites or end users needs to be

[7] This is the only commercial scale direct CTL project in the world. Therefore it is included in this gasification paper.

calculated on a case by case basis. As mentioned previously, the existing hydrogen and chemical plants are relatively small in size compared to coal fired power plants and, in most cases, are located either in a chemical production area or coal reserve. Hence, it is easier to fit in and test carbon dioxide capture equipment in such plants rather than installing the larges size capture equipment to coal fired power plants for early trials of CCS. Having these plants retrofitted could be an easier option than retrofitting the large size power plants. Carbon dioxide could be either consumed locally or transported to other users still at a competitive price.

Chen and Wu (2004) indicate that China should produce most of its liquid fuel from coal for energy security reasons. Coal to liquid and coal to chemical plants have been proposed and built mostly in coal production areas. Capturing carbon dioxide from CTL plants is the next cheapest option when the gasification process is used. The special requirements for capture ready designs for CTL plants are due to the physical properties of the waste gas. According to Mantripragada (2008), the average carbon dioxide to liquid fuel ratio is 0.57 tCO_2/barrel of oil and the ratio of carbon dioxide to coal consumed is about 1.2 in a process where coal is first gasified before the F-T reaction. According to EPA (2007), even with carbon capture and storage, the greenhouse gas emissions from a CTL plant are still 4% higher than ordinary gasoline. And the greenhouse gas emissions from CTL plants without CCS are 118.5% higher than ordinary gasoline. Therefore, CTL plants not only offer a cheaper option for carbon dioxide capture, but also have a social responsibility to make sure they can install a carbon capture unit.

Figure 2-3 shows CTL or coal to chemical (CTC) plants that have installed, or will install, GE or Shell gasifiers. All of the approved CTL plants are in close proximity to the large coal reserves in Inner Mongolia.

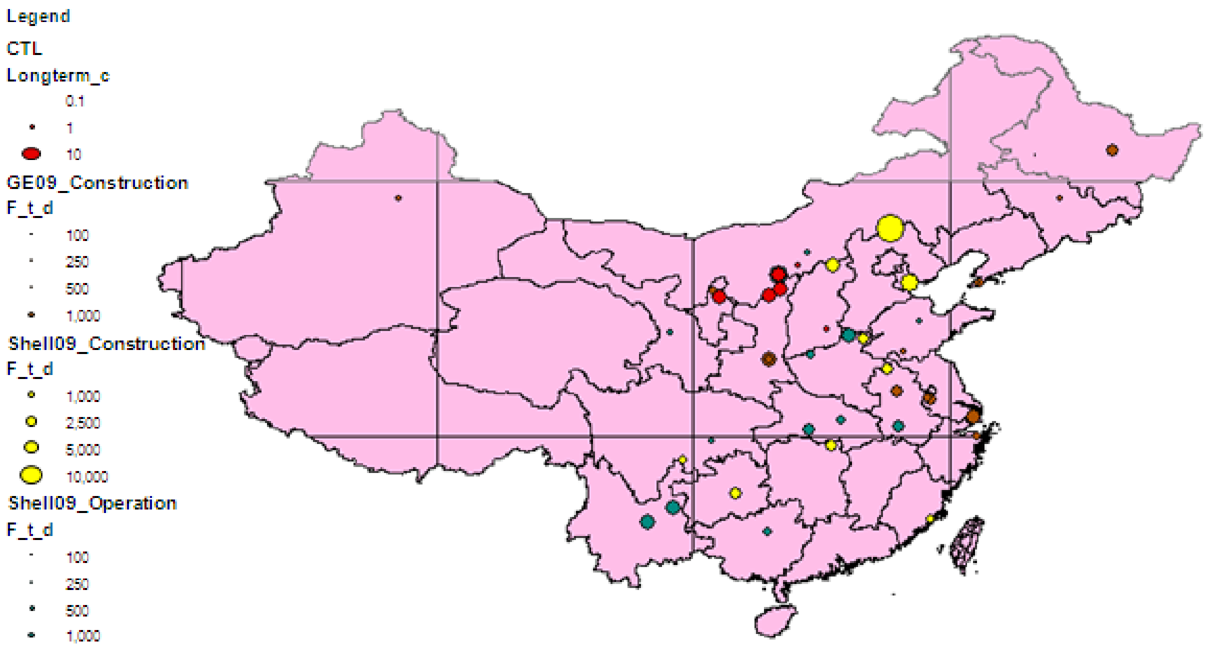

Figure 2-3 GE or Shell technology gasifiers and CTL plants in China (Data from NETL 2009)

Modern gasification technology normally means a much bigger coal input rate, higher oxygen consumption, higher temperatures and higher pressure than conventional small-scale gasifiers. It can also produce higher value chemical products at a much larger scale. The cost of carbon capture is slightly higher than hydrogen plant, but with a better carbon conversion rate inside the gasifier, and a bigger coal input. Differences between entrained-flow gasifier technologies can affect the overall efficiency of the gasifier, such as whether it is a dry feed or a slurry feed, whether it has a quench process before the gas comes out. But in all cases, with more coal going into the gasifier, more carbon dioxide can be captured with consequent economies of scale for transport and storage. A list of coal to liquid plants is shown in

Table 2-3. These represent a growing industry in China that uses advanced gasifiers in coal production areas and at a much bigger scale than normal chemical plants.

Table 2-3 Proposed CTL plants in China (Li 2008)

Company	Location	Current Capacity (liquid fuel) Mt/y	D/I[8]	Operation time	Longterm capacity (Liquid fuel) Mt/y
Shenhua	Inner Mongolia	1	D	End of 2008	5
Yankuang	Shanxi	1	I	2010-2011	5
Luan	Shan'xi	0.16	I	Aug-08	0.48
Yitai	Inner Mongolia	0.16	I	Sep-08	0.48
Shenhua_Sasol	Shan'xi	3.2	I	2013-2014	6
Shenhua_Sasol	Ningxia	3.2	I	2013-2014	6

Mantripragada et al. (2008) have calculated that in order to produce 50,000 barrels of liquid fuel from coal, 28,400 tonnes of carbon dioxide will be emitted. A barrel equals to 158.9 litre of oil with an average density of 0.8kg/L. That is to say, if all six of the current indirect CTL plants reach their highest production capacity, then roughly 102.7 million tonnes of carbon dioxide will be emitted into the atmosphere annually.

Carbon capture and storage prospects are not only important for current plants, but also essential for the CTL plants in planning, since the long-term capacity is much greater than the current capacity. At the moment, only the Shenhua direct liquefaction in Inner Mongolia has announced that they will consider carbon capture ready for their plant. In the Fisher-Tropsch process at indirect liquefaction plants, a large amount of hydrogen is used for reaction. High concentration CO_2 normally emerges when H_2 is produced. That which is not needed in the next process could be captured using similar methods to those mentioned in the previous sections. Because of the large quantities of carbon dioxide at the plants, local consumption or small tests at nearby saline aquifers is not enough. Geological storage potential

[8] D: Direct liquefaction; I: Indirect liquefaction

investigation is the key to making those plants capture ready (as shown in Figure 2-4).

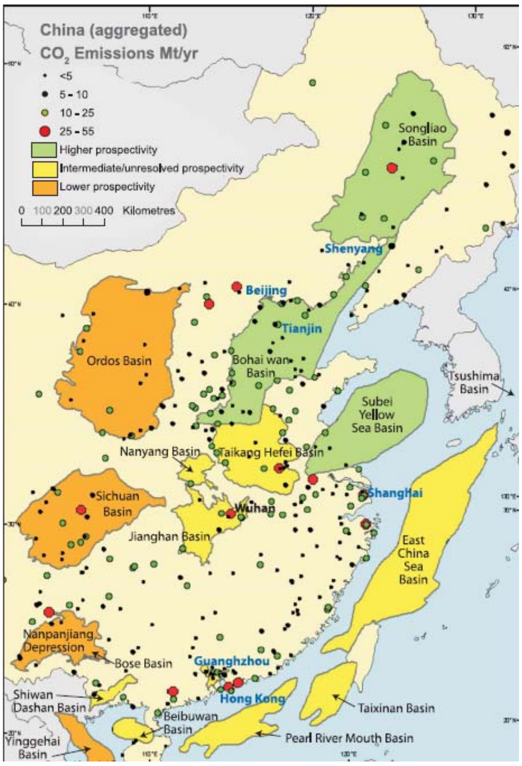

Figure 2-4 Relative prospectively of the geological basins studies with aggregated CO_2 emissions (Bradshaw and Dance 2004)

2.3.4 IGCC plants

Although pre-combustion capture from IGCC plants is considered one of the main options for carbon capture and storage, making IGCC plants capture ready is calculated to be not economically viable and technically difficult in most relevant studies (Griffiths and Scott 2003; Rutkowski, et al. 2003; Li 2008). There is the possibility of adding post-combustion capture units to the IGCC plants after the energy from the syngas is consumed, and after the gas turbine and steam turbine, before going into the atmosphere. The Datang Dongguan plant listed in Table 2-4 from the proposed IGCC plants has a long term plan of expanding the IGCC plant to a post combustion carbon capture plant (Li 2009). In the Greengen Tianjing I project, a post-combustion test system will be added for testing the capture technology, and for the Greengen Tianjing II project, part of the syngas will be extracted for pre-combustion capture in a long term.

Table 2-4 Proposed IGCC plants in China (Li, 2008)

Company	Location	Capacity (MW)	Year	Notes
Yantai IGCC	Yantai (Shandong)	2* 300-400	Planned in 1999	The earliest planned IGCC plant, but has not yet been built (Shell Gasifier)
Greengen	Tianjing I (Lingang Industry zone)	250	2011 (2007)	Coal consumption: 2000t/d; TPRI 2 stage dry feed gasifier; 20% polygen; 80% electricity
Huaneng	Shantou (Guangdong)	100	Planned in 2007	Retrofit a heavy oil plant; Postcombustion capture 10% of the flue gas; TPRI gasifier
Datang	Dongguan (Guangdong, Mayong)	1600 (4*400)	2011	No plan for CO2 capture yet; 13b (CNY)
Greengen	Tianjing II	2*400	Planned in 2007	MOU with Tianjing Government

2.3.5. Theoretical polygeneration concepts

Chiesa et al. (2005) have analysed the performance and emissions on the co-production of electricity and hydrogen with carbon dioxide capture with an entrained-flow gasifier. In their model, the H_2/electricity rate was varied by changing the steam/carbon ratio or by letting the de-carbonised syngas bypass the pressure swing adsorption (PSA) unit. Jin et al. (2007) propose a system for MeOH and electricity with carbon capture, which removes the shift process and replaces it with a chemical island to produce MeOH. The un-reacted syngas is separated, one stream goes back to produce MeOH and the other stream goes to a smaller scale shift reactor for carbon capture process with electricity generation. Lin et al. (2009) further investigate the thermodynamic and economics of MeOH and electricity production. As a result of the system integration between the MeOH production and the electricity production, the system with syngas partly recycled to the methanol reactor can achieve 18.8% of primary cost saving compared to the plant which only produces MeOH and captures carbon dioxide in a conventional process. Li et al. (2010) also analyse the potential for using methanol as hydrogen carrier in the transition process to a hydrogen economy in China.

The above studies combine solid theoretical polygeneration concepts with modern entrained-flow gasifiers. The flexible product and economical investment will play a more important role when the polygeneration concept is more fully adopted, and the market will expand with the successful running of the large scale CTL plants. Carbon capture or capture ready design is considered in most of the polygeneration designs as it is a relatively new concept compared with other gasifier implementations. However, because of the ban on approving new CTL plants due to water consumption and high consumption on coal, the concept has only been developed in scientific papers so far (NDRC 2008).

2.4 CCS for gasification industry

China has most of the world's fixed-bed gasifiers. It is also constructing entrained-flow gasifiers at an extremely high rate, and the probability of China maintaining its fast construction rate in gasifiers is high. Although not many projects have included carbon capture and storage in the expansion or designs of the plan, carbon capture and storage has been taken into consideration by some of the gasifier operators in China. Capturing carbon dioxide from hydrogen plants or chemical plants where a high concentration of carbon dioxide is currently being emitted into the atmosphere constitutes an early opportunity for CCS in China. Carbon capture from fertilizer plants that have carbon dioxide in the flue gas in varying concentrations, should consider the capture option based on different processes. For CTL plants, carbon capture should be considered when the plants are being built since the amount of coal used in CTL plants is enormous compared with plants mentioned previously. The large amounts of carbon dioxide produced in CTL plants can result in cost effective capturing compared with capturing from different sources. The amount of carbon dioxide that can be captured from polygeneration plants varies when the product changes. However, polygeneration plants are one of the early pioneers to have taken carbon capture and storage into account in the planning stages in the gasification industry in China. If IGCC plants are proposed in China, carbon capture units should be installed from the plant's beginning to demonstrate the cost benefits of such technology.

Carbon capture from gasification processes should be taken more seriously in China in comparison with PC, for, when carbon capture becomes mandatory in the future, carbon dioxide produced from gasification streams will be relatively cheap. Hence, when planning a large-scale carbon mitigation roadmap, gasification plants should definitely be taken into consideration. In fact, they should play an essential role in the roadmap.

2.5 Capture ready for gasification plants

2.5.1 Capture ready for IGCC plant (based on co-authored paper, Gibbins et al., 2006)

In addition to the basic space requirement, the scope for pre-investment to reduce the costs of adding capture to IGCC needs to be considered. The fundamental problem in making IGCC plants capture ready is that adding a shift stage will, in general, reduce the chemical energy available in the product gas and increase the heat available as steam. Designing to accommodate this will require equipment to be oversized, with an additional capital cost of perhaps 5%. The alternative, operating at a reduced output after capture is added, also increases capital costs with capture by approximately 2% (Table 2-5).

Table 2-5 Comparison between Jacobs (Griffiths & Scott, 2003) and Parsons (Rutkowski et al., 2003) capture ready IGCC concepts (from Gibbins, 2007)[9]

Jacobs Engineering Capture Ready IGCC

	1A	1B	2A	2B
Coal Feed rate AR (t/h)	160	172	173	168
Steam Turbine (MW)	246.9	241.3	254.6	233.4
Gas turbine (single) (MW)	197.0	194.4	197.0	197.0
Power Output (nett) (MW)	559	489	576	472
Efficiency (%) **LHV basis**	42.2	34.3	40.3	34.0
Heat Rate (HHV) (Btu/kWh)	8384	10296	8777	10395
Capex $MM	650.8	739.5	672.9	728.1
Capex $/kW	1164	1511	1169	1542

5% extra fuel for capture ready IGCC

+2% capital for capture ready plant compared to plant built with capture

Parsons Corporation Capture Ready IGCC

	Baseline CVX IGCC Plant Dual Train	Operating CVX IGCC Plant Retrofitted for CO_2 Capture Derated 90% Capture	Pre-investment CVX IGCC Plant Oversized Dual Train	Pre-investment CVX IGCC Plant Retrofitted for CO_2 Capture 90% Capture
Performance				
Coal Flow, lb/hr	370,663	370,663	370,663	390,950
Total Oxygen Flow, lb/hr	375,574	375,574	375,574	393,747
Gas Turbine Power, kW	394,000	374,480	394,000	394,000
Expander Power, kW	13,950	11,090	13,950	11,600
Steam Power, kW	206,950	191,260	206,950	201,870
Total, kW	614,900	576,830	614,900	607,470
Total Auxiliaries, kW	105,620	152,000	105,620	158,620
Net Power, kW	509,280	424,830	509,280	448,850
HHV basis Efficiency, %HHV	35.4	29.5	35.4	29.5
Heat Rate, Btu/kWh HHV	9,653	11,569	9,653	11,550
CO_2 Captured, lb/hr	N/A	839,372	N/A	885,381
Cost				
Total Plant Cost, 1,000 $	$589,896	$678,196	$619,600	$682,953
Total Plant Cost, $/kW	$1,158	$1,596	$1,217	$1,522
Delta Cost of Retrofit, 1,000 $		$88,300		$63,353
Fixed Operating	$10,806	$11,560	$11,055	$11,586
Variable Operating	$13,837	$14,878	$14,547	$15,173
Fuel @$1.35/MMBtu)	$51,157	$51,144	$51,157	$53,947
COE, $/Mwh[a)]	$45.74	$59.32	$47.09	$57.23

COE based on TPC plus owners costs annualized at a rate of 15% and a 90% capacity factor

+5% capital for capture ready before capture

+5% capital for capture un- ready after capture

[9] These two studies were used as the only examples from the literature that were identified at the time the paper was written (and subsequently) that examined capture ready IGCC and related the energy changes because of the additional capture system. And also gave IGCC plant cost assessments.

If any significant time elapses before capture is fitted, this trade-off therefore obviously does not represent a satisfactory return on initial pre-investment expenditure. An alternative approach, developed by Jacobs, is to incorporate a shift stage from the outset, with losses minimised by some heat recovery as chemical energy and additional shift/gasifier thermal integration. In this case, efficiency is reduced slightly before capture but capital costs before and after is not significantly affected. Whether the resulting increased fuel consumption (~5%) will offset the saving in capital cost for adding capture will depend on local fuel costs and the period of time before capture is added.

In the Jacobs Engineering capture ready assumption, case 1A is the baseline IGCC plant, 1B is the baseline plant retrofitted for CO_2 capture, case 2A is the capture ready IGCC plant, case 2B is the capture ready plant retrofitted for CO_2 capture.

2.5.2 Capture ready CTL plants

In the indirect liquefaction process, a shift process needs to be added in order to hit the target H_2/CO ratio in the feed for the Fischer-Tropsch synthesis reactor. In the direct liquefaction process, a shift process is needed for the production of hydrogen to react with the coal. Therefore, a high concentration CO_2 stream is available and can be stored by adding a compressor and pipeline system to the storage site. For those plants, a reserved space for the compressor is adequate. In a polygeneration plant producing electricity or hydrogen after the F-T synthesis stage, pre-combustion capture can be added before the final stage in order to produce a higher concentration of H_2 (Davison 2008)

2.5.3 Conclusion

Given the wide range of gasifiers used in China, it is difficult to identify the corresponding capture technologies and technology modifications that might be implemented for individual gasifiers. One of the possible approaches that could be used as guidance for such technology has been summarised in Table 2-6.

Table 2-6 CCS and capture ready considerations for different types of gasifiers

	Fixed-bed		Fluidised –bed	Entrained-flow
Usage	Hydrogen, ammonia, urea production		Produce industry gas	MeOH, chemical products and electricity
Oxidant	Intermittent process	Continuous process	Oxygen and steam	Oxygen and steam
	Air or steam	oxygen or oxygen enriched air		
Capture ready design	Easy, as most equipment could be added after the hydrogen or ammonia production plant		Medium, especially when the end product is industry gas, as this could change the end user's gas contents. Hence need to be treated on a case to case base.	Difficult, depending on the end product. MeOH and chemical products are easier than when producing electricity
Capture ready demand	Low, because not many plants are at planning stage		Low, because not many plants are at planning stage	High, as the amount of carbon dioxide emitting from one site is huge and a lot of plants are at planning stage.
Capture retrofit design	Easy, but highly depend on the concentration of the nitrogen presented in the waste gas, the scale for most plants are small and relatively easily managed		Medium to difficult, because it might involve changes for the end users, which could be expensive and cause extra spending with new equipment adding to the end user side.	Easy if the current plants are built in a capture ready statues. Even plants that are not built in the capture ready statues could still be retrofitted relatively easy compared to pulverised coal fired power plants.
Capture retrofit demand	Low, as finance could be an issue for individual plant. But these type of plant could be easily retrofit when financial subside is presented.		Low, as finance could be an issue for individual plant.	High, especially when the new plants need to consider their greenhouse gases emissions in the future.

Fixed-bed gasifiers, which are normally used in hydrogen, ammonia, urea production, where the carbon dioxide in the waste gas is normally high, could be treated as an early opportunity for CCS. The capture ready design and capture retrofit is relatively easy, but given the plants are normally small in terms of production rate, extra financial incentives are needed for CCS. The entrained-flow gasification technology is currently the state of art technology and it normally means plants with large capacity compared with other type of gasification technology, but small when compared with pulverised coal fired plants. These could be an early opportunity for CCS when the decision is between a PC plant and a gasification plant. However, the design for such plants is complicated if compared with other type of gasification technology. The advantages when compared with other types of gasification technology is that entrained-flow gasification plant operators generally have access to finance, and most of those plants have concerns about greenhouse gases emissions from the approving body, which could make CCS development much easier than on other types of plants.

The fluidised-bed plants sit between the fixed-bed and entrained-flow gasification plant, they could have the advantages or disadvantages of those two technologies but might not have a promising long term future compared with the entrained-flow gasification technology. However, they should not be left out when gasification technology is being considered.

The cost of capture in gasification process systems is projected to be significantly lower than the cost of capture from PC plants (Meng et al., 2007). For IGCC plants, it is widely recommended that new plants should be built with capture, rather than capture ready (Rutkowski et al., 2003), since in a capture ready IGCC it is hard to match the gasifier and the turbine both before and after capture and also this approach cannot demonstrate a great saving in the overall capital cost.

Although most of the gasification technologies can be considered as early demonstration opportunities, the potential for capturing carbon dioxide from gasification plants is not as great as capturing from pulverised plants in China due to the amount of carbon dioxide available and the time scale for large gasification development. Gasification project development is also far slower than pulverised coal plants. Hence, the focus for the thesis moved to the pulverised coal plants in the later chapters, especially when considering the risk of carbon lock-in in large stationary emission points in China.

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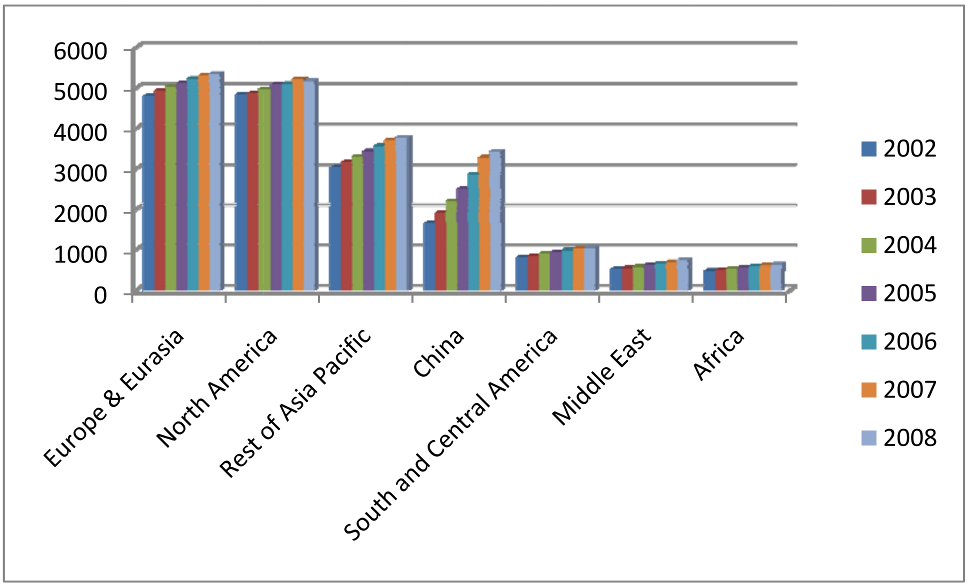
Chapter 3 Chinese Electricity Industry Overview and Forecast

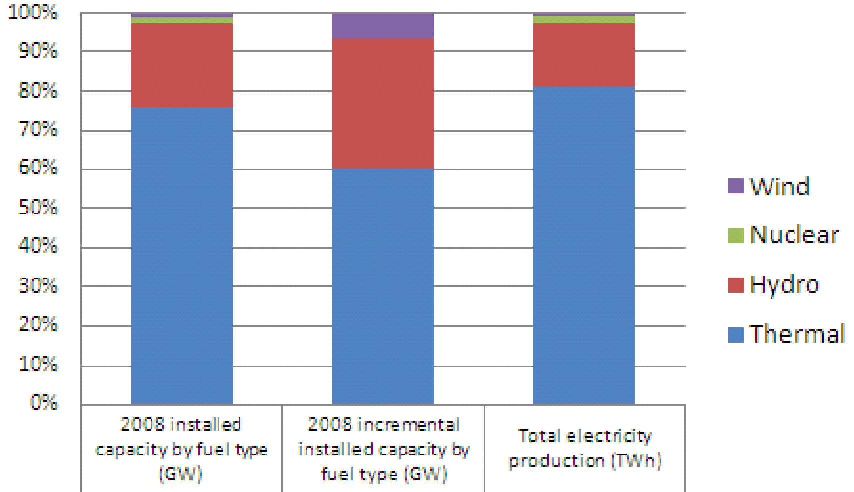
The previous chapter investigated the potential of CCS from gasification plants in China. As discussed, gasification for power generation is still in a demonstration phase in China and the total carbon dioxide emissions from gasification plants is very limited compared with conventional pulverised coal plants. Therefore, the follow-on study changed the focus to pulverised coal plants and post-combustion capture technology, as described in this chapter.

3.1 Chinese Electricity Industry Overview

Chart 3-1The World's Electricity Consumption by Region (in terawatt-hours) (BP 2009)



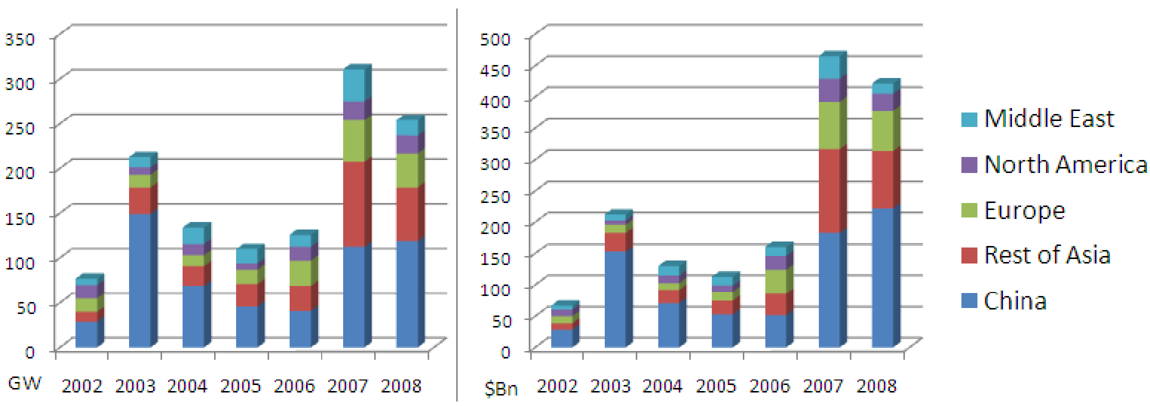
Ten years of sustained economic growth at an average rate of above 10% has not only resulted in a threefold rise in China's real GDP, but also a doubling of total installed electricity generation (NBSC 2009; CEC 2009). China has managed to build over 400 GW of installed capacity in the past 5 years (CEC 2010), equivalent to the last three decades of capacity additions in the US (EIA 2010). Chart 3-1 sets forth the world's electricity generation by region. Coal-fired power dominates in the mix of Chinese electricity sources. As illustrated in Figure 3-1, by the end of 2008, the total installed capacity of conventional thermal power was 601.3 GW (76% of total), of which over 550GW was coal-fired capacity; hydropower constitutes virtually all of the remainder (171.5 GW or 22%) while nuclear (8.9 GW or 1%) and wind (8.9 GW or 1%) each contribute very small shares (CEC 2009).



	2008 installed capacity by fuel type (GW)	2008 incremental installed capacity by fuel type (GW)	Total electricity production (TWh)
Wind	8.9	4.91	13
Nuclear	8.9	0	68
Hydro	171.5	26.26	563
Thermal	601.3	46.9	2779

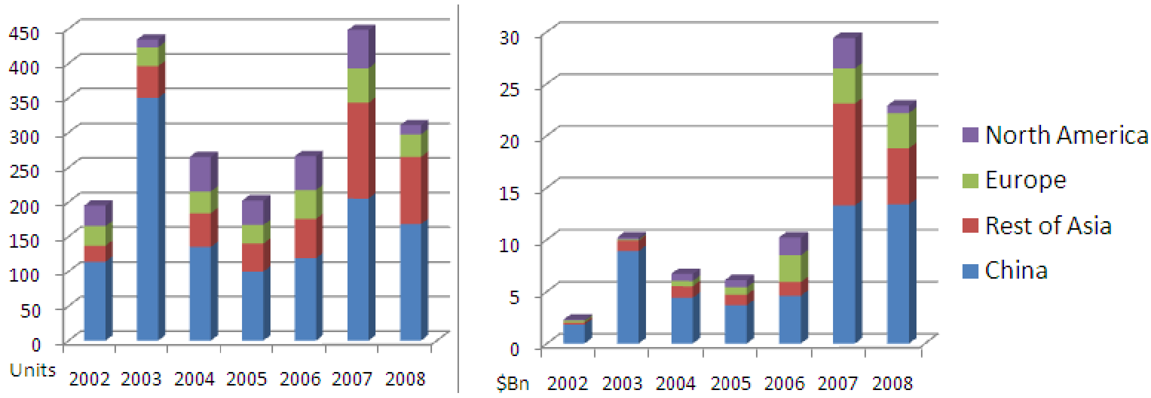
Figure 3-1 Overview of Chinese Electricity Sector in 2008 (CEC 2009)

Chart 3-2 Power Equipment Investment Determined by New Orders (McCoy 2009)



China is currently the largest power equipment market in the world (Chart 3-2). Approximately half of the new power equipment ordered is planned for use in China. This is currently mainly being driven by rising GDP and increasing access to electricity, but will increasingly be driven, it is expected, by climate change priorities and a desire to reduce reliance on coal (for nuclear, wind, hydro) and the need for greater energy efficiency in fossil fuel use.

Chart 3-3 Power generation boiler market size of the world's largest markets by region (McCoy 2009)



China has been the largest large coal fired power plant market in the world for the last decade (Chart 3-3). In 2008, more than half of the world's power plant boiler orders came from China. Especially after the major power shortage in 2002 to 2004, power companies made considerable investments in coal-fired power plants, which led to a significant increase in 2003. According to Frost and Sullivan (2009), each region of the world has a different trend in terms of demand for new boilers in comparison with demand for refurbishing existing units. In North America, refurbishing existing boiler units is forecast to account for 80% of sales, as large-scale new orders are unlikely until carbon legislation has been resolved. In China and Europe, new build is a preferred option, accounting for more than 70% of sales, due to the demand for replacing old fleets. The Chinese central government prefers power companies to decommission existing small units and rebuild them with larger turbines and higher overall capacity, as will be discussed in section 3.2. In terms of the type of units, pulverised coal-fired power plants dominate the investment in thermal power and a majority of newly built coal-fired power plants are ultra-supercritical[10] units (CEC, 2009).

Table 3-1 Total Installed Capacity and Net Power Generation by Region in China as of June 30, 2009 (CEC 2009)

	Total Installed Capacity(with unit capacity over 6000KW)	Net power generation by all power sources		Total Installed Capacity(with unit capacity over 6000KW)	Net power generation by all power sources
	(MW)	(GWh)		(MW)	(GWh)
Guangdong	53490	141532	**Anhui**	27940	33134
Jiangsu	54480	119264	**Guangxi**	23310	31542
Shandong	58070	95952	**Beijing**	5820	30440
Hebei	34480	94165	**Shaanxi**	19840	27469
Zhejiang	48430	93394	**Gansu**	16200	26524
Henan	46550	79416	**Heilongjiang**	18190	24442
Liaoning	23270	54676	**Tianjin**	7510	21927
Inner Mongolia	49900	51195	**Jiangxi**	11670	21321
Guizhou	25300	50771	**Jilin**	14290	18975
Sichuan	31920	44155	**Chongqing**	10430	18812
Shanxi	37040	44030	**Ningxia**	9590	15518
Fujian	24960	43771	**Xinjiang**	10930	13968
Shanghai	16850	41483	**Qinghai**	9120	12637
Hubei	42300	39852	**Hainan**	2850	4790
Yunnan	20560	39397	**Tibet**	n/a	n/a
Hunan	23350	36141			

[10] Ultra-supercritical power plant: the steam temperature is normally 600°C or higher and pressure is over 26MPa. Supercritical power plant: the steam temperature is normally between 570°C to 580°C with pressure between 24 to 26 MPa. Both the ultra-supercritical and supercritical power plants operate above the steam/water critical point. The result for operating at a higher steam temperature and pressure is that less coal will consume in order to generate the same amount of electricity so the power plant has a higher efficiency.

As a result of significant investment in power equipment in China, the growth in installed capacity in China has outpaced demand for power generation since 2005. This trend has caused utilization hours to decrease from an average of 5285 (60.3% in load factor[11]) in 2004 to 4560 (52.1% in load factor) in 2008, according to China Electricity Year Book (2008). Industrial consumption of electricity accounts for 74.5% of Chinese electricity consumption. Table 3-1 sets out the total power installed capacity and net power generation in each province and municipality in China, through which the regional differences of demand and supply can be observed. Although Guangdong has lower total installed capacity than Shandong and Jiangsu, the net power generation in Guangdong is 48% and 19% higher respectively.

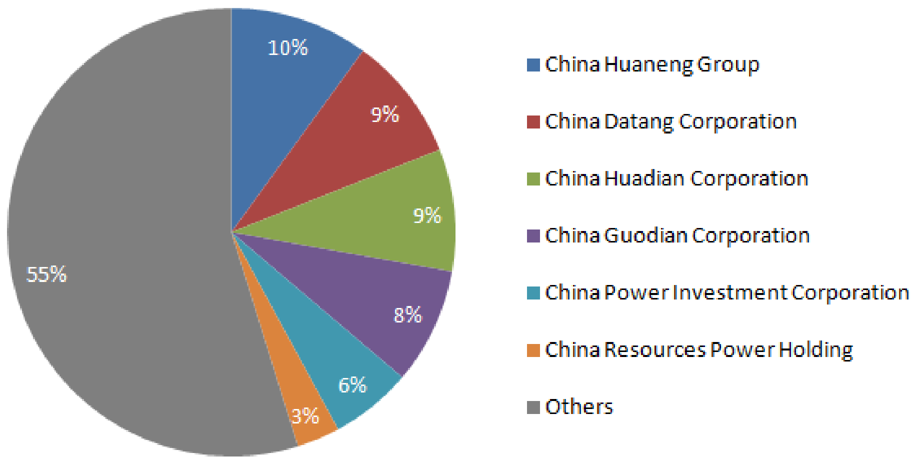


Figure 3-2 Power Installed capacity in the PRC Controlled by Six Largest Independent Power Generation Groups

As of 2007, the largest five state-owned electricity generation groups and China Resources Power Limited have owned and managed approximately 45% of the total installed capacity in China (Figure 3-2). The remainder is primarily owned by provincial and local power companies. The main system for transmission and

[11] It is assumed in chapter 5 in the ASPEN simulation modelling that the power plant will run in full capacity in order to make up the potential electricity lost after a power plant is converted to a CCS plant. It is also a general opinion in the industry that plants with CCS will run in a higher load factor due to its great benefit for climate change mitigation. In this case, the current estimation for new built units in the next 20 years could remain the same.

distribution of power in China consists of the State Grid and the Southern Grid (Table 3-2). All electricity is despatched by power grids companies, except for plants permitted to not be connected to power grids. Power plants liaise with relevant local power grid companies and local authorities annually to determine the volume of output to be dispatched. The electricity dispatched to each grid is administered by dispatch centres owned and operated by grid companies.

Table 3-2 The aggregate installed capacity of the power plants connected to the power grids as a percentage of the total installed capacity in the PRC, and the total electricity generated on those grids as a percentage of the total electricity generated in the PRC in 2007. (CEC 2008)

Power Grid	2007	
	Installed Capacity (%)	**Electricity Generation (%)**
State Grid	**81.0%**	**82.1%**
East China Power Grid	24.2	24.4
Central China Power Grid	22.7	20.4
North China Power Grid	19	21.4
Northeast Power Grid	8.2	8.5
Northwest Power Grid	6.9	7.4
Southern Grid	**18.9%**	**17.8%**
Guangdong Provincial Grid	8.7	8.7
Guizhou provincial Grid	3.2	3.2
Yunnan Provincial Grid	3.3	2.9
Guangxi Provincial Grid	2.9	2.2
Tianshengqiao Plant	0.4	0.4
Hainan Provincial Grid	0.4	0.4
Nationwide total	100	100

China is currently a developing country party of the Framework Convention on Climate Change, and, as such, has no emissions reduction targets for greenhouse gases. However, deploying low carbon electricity has received great attention by a majority of energy producers, consumers and equipment manufacturers in China

(Liang et al 2008). EIA estimates that China's total emissions from coal use have already exceeded that of the OECD, reaching 41% of the world's total and will reach more than half of the world's total by 2030 (Figure 3-3), although Chinese average per capita emissions remains at only two-fifths of the Organisation for Economic Co-operation and Development (OECD) level (EIA 2010).

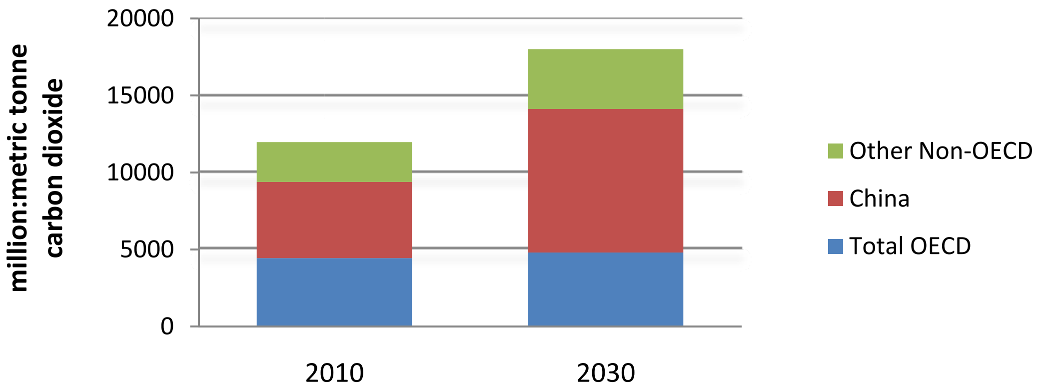


Figure 3-3Global Total CO2 Emissions from Coal Use (EIA, 2010)

Although China is considered as a country rich in coal reserves, the summer peak benchmark coal price (6800kCal, Qinghuangdao in the end of August) has increased from $52/tonne in 2006 to $165/tonne in 2008 and remained at $90/tonne from during soon after the credit crisis in 2009 (Bloomberg 2009). Therefore, energy efficiency has been of greater interest in China since 2006 (Andrews-Speed 2007). To support the national energy efficiency target, policies such as 'replacing small units by large units' and 'allocate more on-grids electricity quota to higher efficiency unit' have been put forward (State Council, 2006).

The development of the Chinese energy sector not only consists of growth in energy supply and consumption but also includes the evolution of a regulatory framework (Reiner and Liang 2009). In the past ten years, China's electricity market has experienced major reforms to promote the role of markets and create effective regulation in the electricity sector. Measures have included separating power plant ownership from the electricity grid operators; restructuring central generation and electric distribution assets, developing regional electricity markets, and establishing a professional, independent electricity regulator (SERC et al 2007). However, currently, the on-grids electricity tariff is still formulated by NDRC (National Development and Reform Commission) and provincial price bureaus (Liang et al 2008).

3.2 Closing smaller plant policy

According to the State Council's policy on reducing energy consumption (State Council 2006), China has set up a target to reduce its energy consumption per GDP by 20% by the end of its 11th five year plan (2006-2010). To achieve this target, NDRC issued a policy to accelerate the closing down of small power generation units. The policy is well known for "encouraging large power generation units and closing small inefficient units" or "Shang Da Ya Xiao" (上大压小) (State Council 2007).

In NDRC's master plan, the defining criteria for small inefficient coal and oil generation units are shown in Table 3-3(State Council 2007):

In the 11th five-year plan, NDRC targets are to close 50GW of small units, mostly coal-fired units, and also 7 to 10GW of oil-fired[12] units. At the same time, firms that have closed small inefficient plants will have priority when it comes to listing their proposed large-scale plants within the national electricity development plan (State Council 2007). If a company wants to build a single unit plant of 300MW, it is required to close down at least 80% of the equivalent capacity of smaller units. But the proportion of old plant that has to be closed down decreases with the proposed unit's size. For example, if the proposed generation unit is 600MW, only 70% of the equivalent capacity of small units is required to be closed down. Moreover, when the unit size reaches 1000MW, the factor will further drop to 60%. That is to say, if a

[12] It is not known, nor likely to be known, whether the plants are combined cycle plants.

company plans to get permission to build a new power plant by 2010, the bigger the new unit, the smaller proportion of old units they will need to close down.

Table 3-3 NDRC definitions on small inefficient units

Definitions	*Comments*
All conventional fossil fuel generation units with a capacity smaller than 50MW;	
Conventional fossil fuel generation units with a capacity smaller than 100MW but more than 20 years' operating period;	
Power plants of all types which have already reached their design lifetimes and where the unit capacity is smaller than 200MW ;	*Design lifetime: 25 years for Chinese power plants, but with the possibility to extend this period if the main structure is still suitable for use at the end of the 25 years.*
All plants with coal consumption per kW 10% higher than its average provincial level or 15% higher than the national level;	*Coal consumption varies by coal types; in this article it is calculated by the equivalent standard coal. When a specific fuel of a certain weight has a Lower Heating Value (LHV) of 29.27MJ, it can be converted as 1kg of standard coal (Dept. of Electricity, 1987);* *Provincial coal consumption levels are shown in Figure 3-5;* *The national coal consumption level is 367g/kWh.*
Power plants that cannot comply with the national environmental standard;	*Such as plants which fail the air pollution standard GB13223—2003 for thermal power plants (SEPA, 2006).*
Other units needing to be closed down by law, regulation and the state council's relevant department.	*This includes the unauthorised plants built in China.*
CHP plants failing to fulfill the coal consumption requirement when only electricity is produced.	

The policy obviously helps to increase the plant efficiency in China. Moreover, it can reduce pollution from small and inefficient plants. Currently, 35% of the SO_2 and 53% of the soot emissions from the thermal power industry are emitted by small thermal power plants (China Daily 2007). After these small units are replaced by large units, coal consumption will be reduced by 18.8 Mt/year, SO_2 emissions by 290kt/year and CO_2 emissions by 37.6 Mt/year (NDRC 2008).

3.2.1 Reasons for closing down small inefficient plant

The World Energy Council (2008) states that improvements in the energy efficiency of thermal power generation can be a significant source of energy saving, since it is still low in most emerging and developing countries. Corresponding to the Chinese national 11th Five Year Plan objective of reducing energy consumption per GDP, the electricity companies are implementing the "closing small plant" policy as their contribution to the national target.

Table 3-4 Coal consumption and efficiency at different installed capacity (Yu 2006)

Installed Capacity (MW)	Coal Consumption for power generation	Electricity Generation Efficiency %	Plant Consumption Efficiency[13] %	Coal Consumption for power supply	Power Supply Efficiency %
12	480	25.6	15	552	22.3
25	440	27.9	13	497.2	24.7
50	420	29.3	12	470.4	26.1
100	400	30.7	11	444	27.7
125	375	32.8	10	412.5	29.8
300	330	37.2	7	353	34.8
600	320	38.4	6	339	36.2
1000	273	45.0	5	287	42.9

[13] Average level for specified installed capacity, which varies by cooling method, plant location. This is percentage of the electricity used in the power plant divided by the total electricity generated

Table 3-4 shows the coal consumption of different installed capacity in China. It can be seen that power plants with a capacity of 100MW only have an average efficiency of 27.67%, which is 7% less than the average efficiency of 300MW units and 15% less than the 1000MW units. Currently, the world average efficiency of thermal power generation in 2006 is 34% (World Energy Council 2008), this is similar to the 300MW units, with coal consumption for power supply at 353g/kWh (Yu 2006). In 2006, the average coal consumption of China's thermal power plants was 367g/kWh, much higher than that of the world average (. Because of the highly successful small units closure policy, coal consumption dropped to 357g/kWh in China in 2007 (CEC 2008).

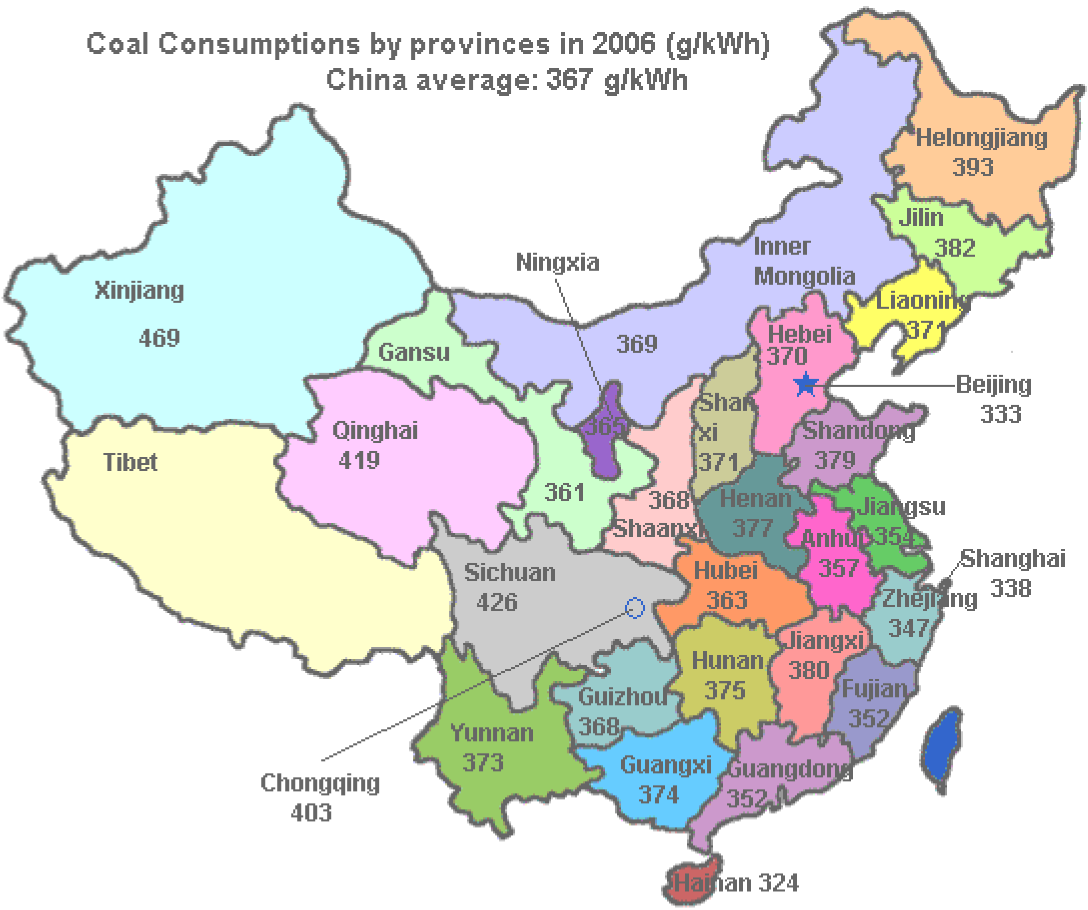


Figure 3-4 Coal consumption by provinces in 2006 (CEC 2007)

The coal consumption rate also varies among provinces (Figure 3-4). Beijng, Shanghai and Hainan have the best efficiency rate in comparison with others. The coastal areas also perform better than the inland regions. The reason for this is that the coastal areas have a better economic environment and more money to invest in higher efficiency advanced units. At the same time, coal resources are not abundant in the coastal areas, and such areas heavily rely on coal imported from the inland or overseas. Hence, enhancing energy efficiency is an effective way of saving resources and reducing costs for coastal areas.

3.2.2 The history of the small size plant

The closure plan, started in 2006, marked the third time that the central government officially set targets to close down small electricity generation units. Both of the two former plans were interrupted because of electricity shortages that emerged whilst the action was being carried out. This is illustrated by a brief description of the electricity demand and supply change in China in the past two decades included in this chapter.

Historically, China has had two waves of small units' construction. The first such construction wave started in the late 1980s and continued through to the early 1990s. At that time, China was short of electricity, especially in rural areas. Therefore, the Chinese central government proposed to build small power units in order to relieve pressure from the electricity shortages and to promote economic development in the countryside. From 1992, the electricity shortage became even worse. The government announced a series of polices (such as guaranteed operating hours, fixed price and guaranteed investment return of electricity) to encourage the building of new power plants. In this period, a lot of private investors, including foreign investors (Liang et al 2008), started investing in the electricity industry in China. By 1996, the electricity supply had exceeded demand and investment stated to slow down. But by 2002 (see Figure 3-5), investment in electricity started to rise again after a series of electricity shortages affected the coastal areas during the summer.

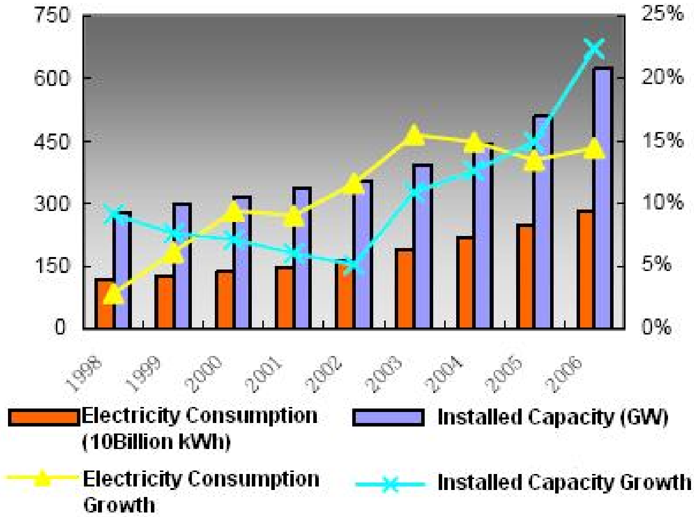


Figure 3-5 Electricity supply and demand in China from 1998 to 2006 (CCXI, 2007)

Table 3-5 2000 – 2005 Power Generation Unit Structure (Wang, 2006)

	2000	2001	2002	2003	2004	2005
Units < 100MW	N/A	N/A	N/A	N/A	N/A	N/A
Total Capacity GW	69.1	71.7	74.8	81.0	88.7	101.9
Percentage of total installed capacity (%)	29.1	28.3	28.2	27.9	27.3	24.0
100MW⩽ Units <	317	328	336	377	414	573
Total Capacity GW	36.2	37.5	38.7	44.7	49.7	70.9
Percentage of total installed capacity (%)	15.3	14.8	14.5	15.4	15.3	16.5
200MW ⩽ Units <	198	202	205	212	218	255
Total Capacity GW	39.8	40.8	41.3	42.9	44.3	53.0
Percentage of total installed capacity (%)	16.8	16.1	15.7	14.8	13.6	12.5
Units⩾300MW	266	295	314	342	394	534
Total Capacity GW	92.3	103.0	110.7	121.2	142.2	119.6
Percentage of total installed capacity (%)	38.9	40.7	41.7	41.8	43.8	47.1

According to Xu (2007), there were nearly 3800 small units of 6MW to 50MW in China by the end of 2004, a total of 46.7GW. In addition, a lot of plants were less than 6MW and were not selling electricity to the national grid. The total capacity of these self-supply plants was estimated to be 15GW. The number of coal-fired power plants with a capacity of less than 100MW was 5619, which made up more than 10 GW of installed capacity in 2005. The small capacity coal-fired power plants made up 24% of the total installed capacity of coal-fired plants (Xu, 2007). A more detailed breakdown of the power plant sizes is shown in Table 3-5.

However, the widely spread small thermal plants caused more serious pollution problems, and had a much higher coal consumption, as a result of low efficiency. In 1995, the central government started to restrict the construction of small plants. In the 10th five-year plan (2000 – 2005), 15 GW of installed capacity were scheduled for closure, but only 8.3 GW were actually closed (C114, 2007) since the electricity shortage in 2003 delayed the plan. Moreover, some areas that suffered serious shortages started building more small units in order to combat the lack of electricity. It can be observed that the construction of small units always began with electricity shortages, which not only brought environmental problems to local residents but also accelerated the coal or oil consumption afterwards. As a result, the government tended to control and terminate small units when the electricity reserve margin was high. The action on closing smaller size plant was suspended temporarily because electricity supply could not meet past high economic growth during 2003 to 2005.

Figure 3-6 shows the number of small plants distributed by owners and the percentage of large units installed by the biggest five electricity companies in China. China Power Investment Corp. (CPI) had the most ambitious target among the ‘big five’; a full 6.82 GW of installed capacity are scheduled for closure, amounting to more than 10% of the overall target in the scheme. China Guodian Corp. (Guodian) is also required to close down 6.29 GW of installed capacity, not much less than CPI.

China Huadian Corp. (Huadian) and Datang all have similar targets of 4.84GW and 4.72GW. China Huaneng Group. (Huaeng) has the most efficient plant among the 'big five' power companies in China, and their small plant capacity is 3.61GW. There are also 1.2GW of small plants owned by the National Grid needing to be closed, and there are over 50% of the 63.5GW of small plant capacity owned by other companies that sell electricity to the National Grid. This 63.5GW is larger than the 50GW closure target over the 5-year period set by NDRC. So whether or not the extra 13.5GW capacity will be closed, or when it will be closed, is yet unknown.

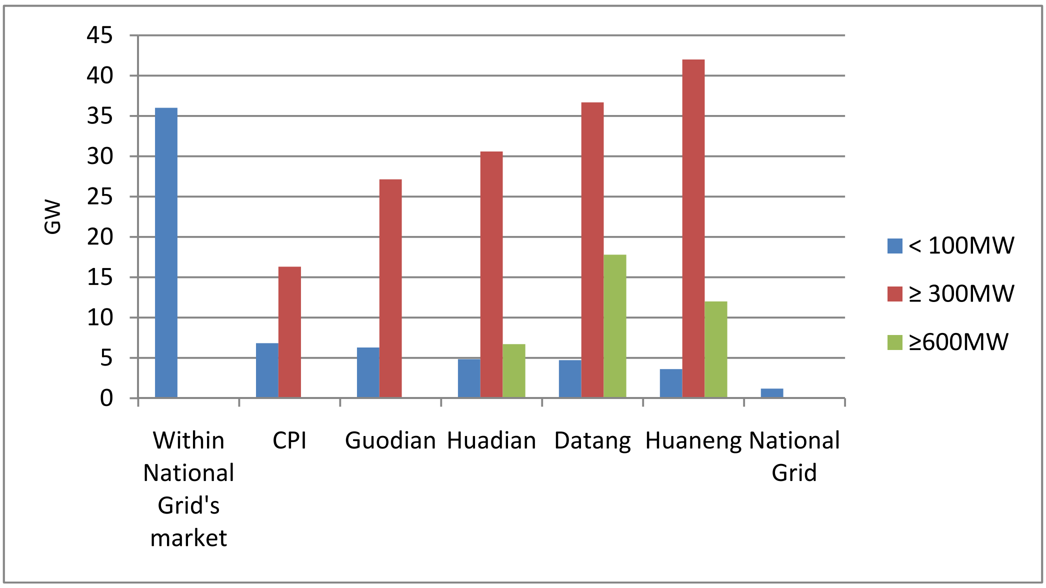


Figure 3-6 The distribution of generation units among the 'Big Five' and National Grid (CPNN 2008; Wang 2007)

For the 'big five' companies, small plants might appear inadvisable because of their high consumption of energy, but they can also bring new investment opportunities. When considering how much bigger the new plants will be, there will be fewer small units in need of closure according to the policy. A large company will have more money than small companies to invest in larger power plants. And small companies can sell their allowance of more generation unit to the larger companies. This is one of the reasons the Huaneng Corp. has promised to close an extra 50% of their small units and has set its target to 3.61GW.

3.2.3 Current progress

In 2006, only 1.212 GW of small power plants were closed, which was equal to around 12% of its original targets of the units' capacity being shut down for that year (NDRC 2006). More than 90% of the plants that were shut were owned by China Huadian Corporation and China Power Investment Corporation. In 2006, electricity supply has just met the demand after a three-year shortage. But in 2007, electricity supply exceeded demand. By December 27th 2007, China had closed another 553 units, with a total capacity of 14.38 GW – 43% more than its 10 GW/year target. 73.1% of the phased out small units belonged to the five largest power companies in China (NDRC 2008). By July 2009, China had closed 7467 units, with a total capacity of 54.1GW, achieving the target it had set one year and five months in advance (People, 2009).

3.2.4 Impacts on power plants yet to be built

The policy has not only changed the unit size distribution in China, but has also refreshed the concept of "the larger the unit the better", for, when power companies close down certain smaller plants, larger sized units, in terms of installed capacity, can be approved. When the policy started to be implemented in China in 2006, the 300MW unit was the most commonly built unit. Currently, no new 300MW units are being approved by NDRC and no standing orders for manufacture of the biggest three boilers for 300MW units are being taken (Linkschina 2008). The most common units being built are the 600MW or 660MW ultra supercritical units. More and more sites are building the 1000MW unit with 45% efficiency in China.

This also stimulates new thinking about the designed lifespan, which is set to be 25 years for power plants in China. Some of the 300MW units might not see their 25 year anniversary if a stricter policy on small power plants comes out in the future. According to Chinese Electricity Council analysis, the consequence of this is that a greater number of large units are being built (CEC 2009). At the same time, this policy has made the capture ready design less complicated, as the predicted new units built from now will be 600MW, 660MW or 1000MW in unit size. Capture ready policies and research for pulverised coal plants in China should focus on the large units.

3.3 Conclusion and pulverised coal plants forecast

The massive amount of coal-fired power plant construction since 2003 due to electricity shortages has resulted in a much shorter plant construction period, similar plant standardised layouts and recognisably identical plant parameters. Both the China Electricity Council (CEC) and the International Energy Agency (IEA) estimates that another 300 GW of supercritical and ultra-supercritical new coal-fired power plants will be constructed in the next decade to satisfy the growing energy demand of the country. Although the Chinese national government has a national target of increasing the utilization of renewable energy, such as wind, solar PV and hydro power, as well as further development and deployment of nuclear power, these power generation technologies are expected to provide only 30% of the total electricity supply by 2030 (Wu 2007). The IEA (2009) quotes unpublished projections by MOST which show that the total generation capacity of coal-fired power plants will reach 1040GW by 2030 and 1200GW by 2030, which is similar to Wu's prediction.

Figure 3-7 shows the electricity installed capacity by different sources of energy from 1990 to 2008 and the estimated changes from 2010 to 2030. The projected increased in coal-fired power plant installed capacity will continue to account for more than 63% of total installed capacity in the foreseeable two decades (Wu 2007), while the IEA (2009) has estimated that 60% of Chinese electricity will be generated by coal-fired power plants in 2030.

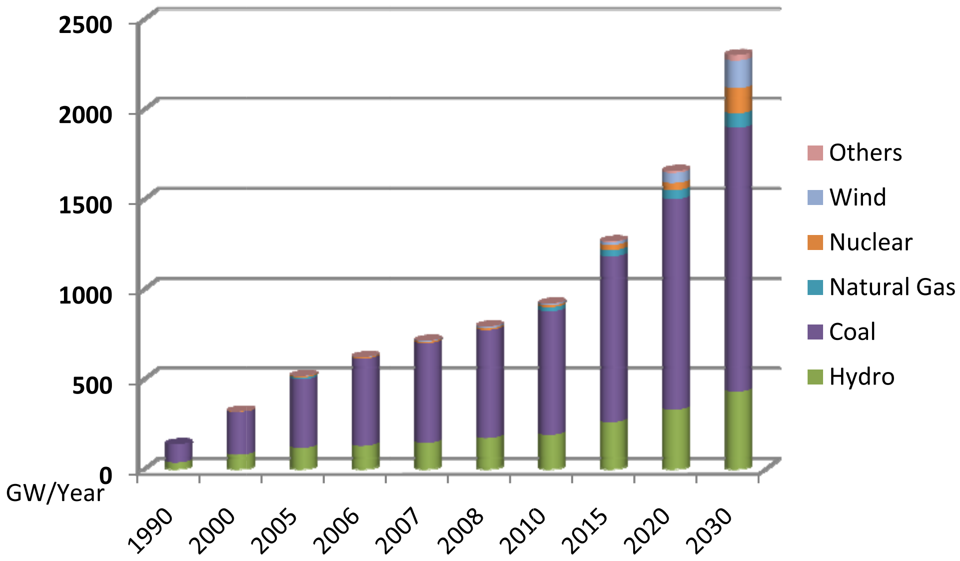


Figure 3-7 Electricity supply 1990-2030E (Wu 2007)

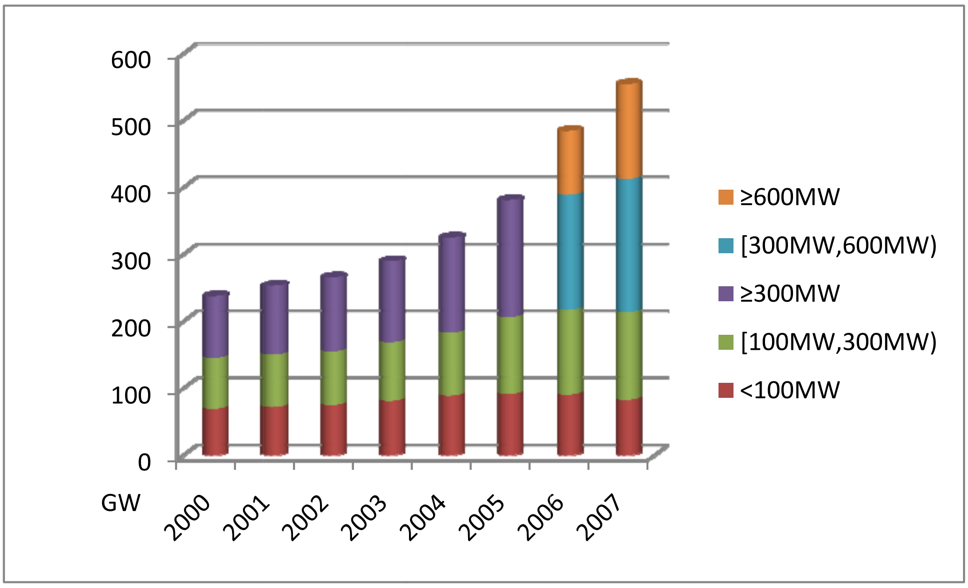


Figure 3-8 Power plant capacity changes for 2000 – 2007 (Linkschina 2009)

Figure 3-8 shows the power plant capacity changes for 2000 and 2007. Before the year 2006, there is no published statistical data for power plants with a unit installed capacity of over 600MW. Therefore, it is not shown in this figure. After the year 2006, the policy of closing down small inefficient power plants and replacing them with the large efficient power plants took place. The policy aims to close down all of the small units, as mentioned in the previous section, and China has achieved its goal in this five year plan.

Therefore, more large plants, especially 1000MW, 600MW and 660MW units will dominate the future boiler market. A more detailed analysis will be undertaken in chapter 5.

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Chapter 4 Carbon Capture Retrofit for Pulverised Coal Plants in China

The enormous pulverised coal fired plants capacity operating in China makes carbon capture, especially capture retrofit sounds like an impossible task. The number of plants is great and China is such a big country in terms of size. However, these difficulties could all be broken down into an easier approach to achieve carbon capture in the long term. Based on past experience of power generation technology and policy implementation in China, the Chinese power industry always aims for larger and more efficient units especially when the economy is still expanding and is forecasted to grow in the next decade. The case of building power plants just to satisfy existing demand, which is common in developed countries, does not seem to fit in the Chinese electricity market. With the government's long term support on increasing power plant efficiency and closing smaller sized plants, we can assume that carbon capture might start in those more efficient plants at the beginning, which normally means large single unit installed capacity. Due to the nature of storage and transport infrastructure costs, bigger sized plants which are built close to each other can share some of the pipelines and storage sites. Hence, power plants located within "electricity generation hubs" will have a cost benefit when retrofitted.

In this chapter, the range of existing power plant size, location and design is explored in order to generate a general picture of large size, advanced technology power plants. The method involves getting power plant layout from satellite images, where available, for all the power plants that are over 1GW in installed capacity at a single site, studying the layout out for the power plants and grouping the power plants by type of location and estimating retrofit potential.

4.1 Power plant retrofit prospects in China based on Google Earth images for current power plants

An investigation of 134 existing power plants layout has been carried out for the study, with the aim of identifying common design and layout features of Chinese power plants. This is the first study of its kind looking at power plant layout for the purpose of retrofitting potential in China.

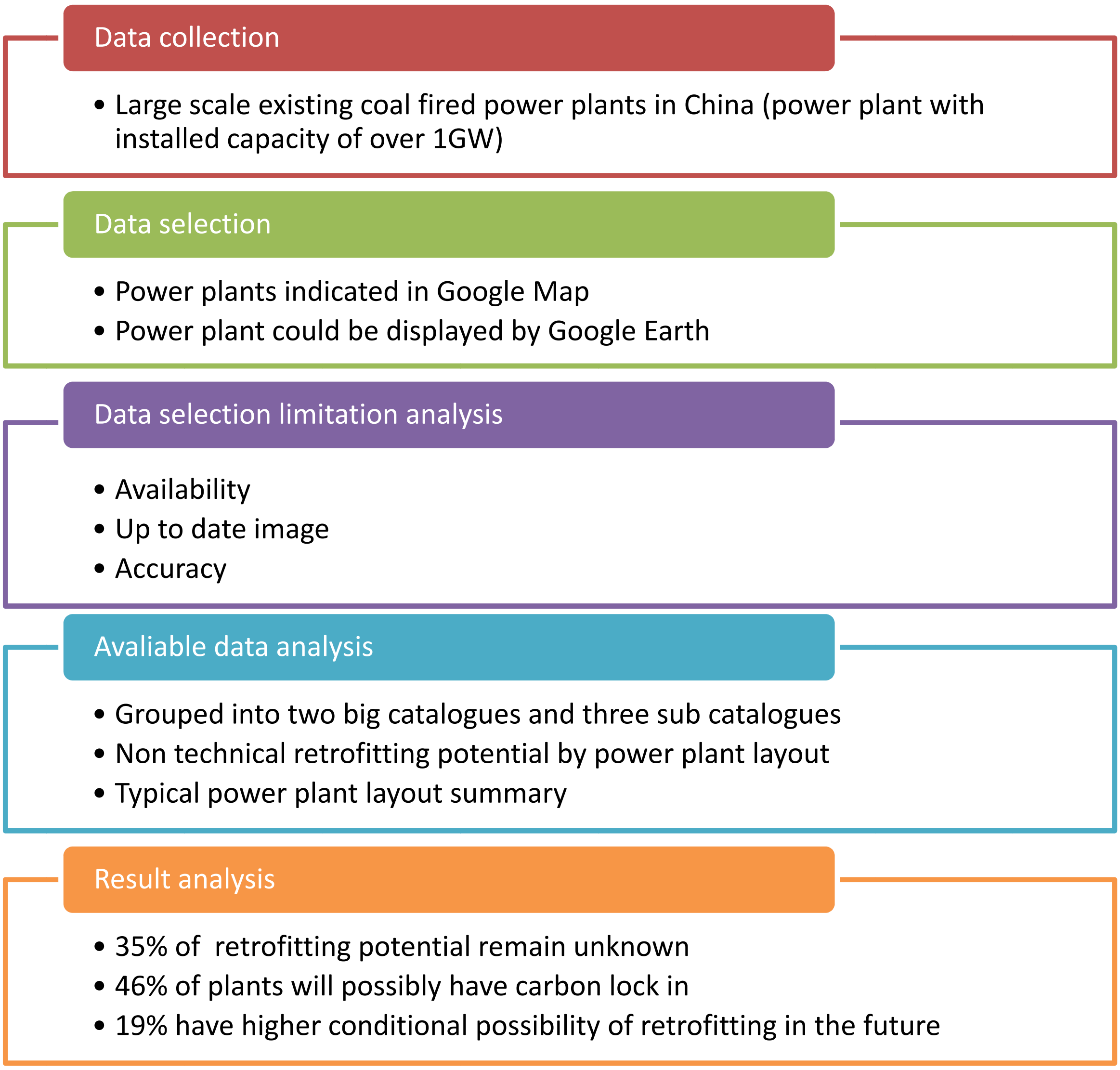

Chart 4-1 Methodology for analysing Google Earth images of power plants

Google Earth was selected as the tool for power plant layout study as it is a free and easy to use software, it was obviously impossible to physically visit a significant proportion of the power plants in China during this study. As new plants are built in the future, a similar study can be carried out using the same software. Some plants that were visited in this study for comparison are shown in detail in section 4.1.3 for further analysis. As mentioned in the Chinese electricity overview section (Chapter 3), the total installed capacity doubled between 2006 and 2009, with most plants being built at the moment having a single unit installed capacity of over 600MW. This growth was achieved by a “photocopying” process, resulting in a lot of similar power plants, in layout and design, in China. The result of this is that while China was building power plants at a massive speed during 2004 to 2009, a lot of them ppear to have a similar layout. This is different from the plants built longer ago, which generally seem to have different layout designs. The methodology for analysing the data is shown in Chart 4-1.

4.1.1 Data selection and sourcing

Based on official information from the China Electricity Council (CEC 2007), the number of coal-fired power plants with an installed capacity of over 1GW reached 164 sites in the year 2006 (see Appendix 1). These have a total capacity of 233 GW, which amounts to 82% of the total installed capacity of coal-fired power plants in China in 2006. The analysis in this section is based on information for these plants. Out of 164, 134 plants could be identified when the address of the power plant was supplied to Google Map. Among these 134 sites, for 74 sites the layouts were clearly shown by Google Earth or Google Map (Google thereafter); for 54 sites there was no clear plant layout image in Google; for the remaining 6 sites no power plants were in existence at the time of the Google survey. These 74 sites with a total installed capacity of 107.7GW are identified in Appendix 1 for further analysis in this study.

4.1.2 Limitations of the study

As summarised above, even though the sample of plants available for analysis is still large in terms of numbers of sites and installed capacity, over half of the total published plants are unavailable for inclusion in the analysis due to the unavailability or lack of definition for Google Earth Images. The main limitations for the study are then:

1. Google Earth cannot identify all the power plants from the database, because of the limited coverage of the satellite images.
2. Some of the Google Earth images are out of date and so do not show the current situation at the plant. As the satellite images were taken at a time in the past, hence some of the plants are showing images taken years before the study. However, this is the most widely used (and free) source of data that is available in the public domain.
3. The time of the satellite photos taken varies between regions. Plants in the more well-developed areas normally have an up to date image displayed in Google, often less than three months old, while for rural areas the images are updated much less frequently. Hence, the comparison of the different power plants is not based at a single time in the past, but at different times based on the availability from Google.
4. The resolution (pixel count) of the satellite images varies greatly in the study. Similar to point 2, the better developed areas typically have higher resolution images than the more recently developed areas.
5. New power plants are being built all the time, for instance, based on the latest information which appears after the study was completed. from the China Electricity Council (CEC 2008), the number of coal-fired power plants with the installed capacity of over 1GW reached 207 sites in the year 2007, with a total installed capacity of 312 GW, which accounts for 84% of all coal-fired plants in China. This is 23% more sites than the data studied in this study. And at the time the study was carried out, the information above was not available.

Results affected by these limitations:

1. The limitation resulting from the availability of the image has resulted in no images being found for 6 (4%) of the plants selected from the database for retrofit purposes. However, these 6 plants are located in rural areas, with no obvious building or village surrounding them on the Google map. Hence, there is still a reasonable possibility of that extra space being acquired by the power plant for carbon capture retrofit in the future.
2. The fact that the satellite image can only demonstrate the situation at a certain point in time prevents an assessment of the current retrofitting potential of the plants, with results only able to represent the retrofitting potential at the time in the past when the photos were taken. However, for plants without any possibility of retrofitting in these historic images, the outcome is very unlikely to change because of the passage of time difference. This is because in the process of city development a developed area is unlikely to be abandoned, except in the case of the Three Gorges Project or in the event of an unexpected natural disaster. But in both cases, there is no need for the retrofit as the power plants would be no longer capable of producing electricity.
3. And 4. This is an unavoidable limitation of the work, but the consequences are probably not very serious because A) the layout is likely to be changed in adjusting to building surrounding it. B) the developing area will have changed by the time of retrofitting it. C) There are other ways of doing it, but the use of Google is probably the cheapest. The low resolution made images from 54 plants unsuitable for assessment for retrofit. Most of the low resolution photos are in areas that are less developed at the moment. Normally some of these ‘old’ areas will become more industrialised, hence reducing the possibility of retrofitting these power plants at a later stage.

5. The area imbalance shown from the image pixel count of the photographs will normally result in some of the old rural areas becoming more industrialised. Hence, there is a reduced possibility of retrofitting the power plants at a later stage within the plant lifetime as most of the low resolution photos are taken from less developed area at the moment. The low resolution has also made the 54 plants unable to be investigated for detail power plant layouts.

6. The increase in the sites with over 1GW installed capacity between 2006 and 2007 (and subsequently) will not affect the total number of power plants built within developed areas. Policy guidelines require that new power plants are built away from developed areas, and also the land cost is much cheaper in rural areas. The percentage of power plants that are within rural areas and thus have a greater potential to be retrofitted is therefore expected to increase in this case. Obviously, these will offset some of the older plants than can no longer be retrofitted, as the area they are located has become more developed.

Although there are these limitations in the data a large number of images showing enough information for analysis are, however, still available. The results are also likely to be generally applicable since amongst the power plants analysed there exist large similarities in layout between different regions.

4.1.3 Data analysis

Two major categories and three sub categories are used to classify the layout of the plants, because space on site is recognised as the primary factor when retrofitting a power plant. All the plants are classified first by the surrounding area condition, either located in a rural area or in an industrially developed area (developed area thereafter). This is used to identify the expansion possibility of the power plant, in order to accommodate additional capture equipment, compression equipment and temporary storage of equipment if necessary. There may be plants which have enough space surrounding them, but the soil conditions are not suitable for construction. However, this is not examined in this thesis, as this is likely to be a very rare example of why a plant would not be suitable for capture retrofit, especially given that a power plant has already been built at the site.

Table 4-1 Power plant classification

Location of plant	**Sub-location of plant**	**No.of plants**	**% within main category**	**%**
Rural Area	Coastal	4	14	38
	River	6	21	
	No obvious water supply	18	65	
Within Industry Zones	Coastal	7	15	62
	River	24	52	
	No obvious water supply	15	33	
Total no. of Google Earth images		74		

The sub categories are defined by the observable water supply/cooling system. Three main water supply/cooling systems are used: sea water, river water and no obvious direct water supply (cannot be seen easily from Google Earth), which means the plant normally uses wet cooling towers at the time of the investigation. The results of the initial analysis are shown in Table 4-1. Around 62% of the power plants that can be identified clearly in Google images are within industry zones. The percentage of coastal power plants in both cases is very similar, in the range of 14 – 15%. The biggest difference is that the percentage of power plants built next to rivers or lakes is significantly lower in the rural areas than in industrial zones. Power plants with no obvious direct water supply in the rural area are over 60%. A possible reason, as discussed elsewhere in the study, could be that plants built earlier have occupied the prime locations for building power plants. Some selected typical images[14] of the power plants are shown and discussed below to illustrate the analysis approach used.

4.1.3.1 Industrial area plant

1. Coastal or river side plant

Figure 4-1 Shajiao ABC Plant, Guangdong, China

The coastal and river side plants comprise 67% of the plants currently located within industry zones or fully developed area. Figure 4-1 shows the Google Earth Image of the Shajiao A, Shajiao B and Shajiao C power plants located in Guangdong, next to the Zhujiang River. These three plants are located adjacent to each other, but belong to three different companies. The earlier of these three, the Shajiao A power plant has its first three 210MW units built in 1987 and another two 300MW unit built in 1996 (SJPS 2010). Shajiao B, which is also built around similar period has two 350MW unit (SEC 2010). Shajiao C, which started construction in 1992, has three

[14] The Tuoketuo plant is selected because it was the world's biggest PC plant, other plants were selected because they were also visited in person by the author.

660MW units. Each of the individual plants is built in a straight line, which is typical in China. These plants are very close to the village shown at the top of the figure and do not have large amounts of land around them. Except for the Shajiao A power plants, the other two plants have a very tight power plant layout. As originally built, Shajiao B and Shajiao C have the same mother company and they are both Built Operate Transfer (BOT) projects from when Guangdong provinces were still facing electricity shortage problems. Retrofitting these types of power plants will be difficult because the price of land is normally more expensive than in the less developed area. The tight layout within a power plant site is also likely to make it difficult to accommodate the capture units. Figure 4-2 shows the view from an apartment of a power plant in the same region (Mawan Power plant).

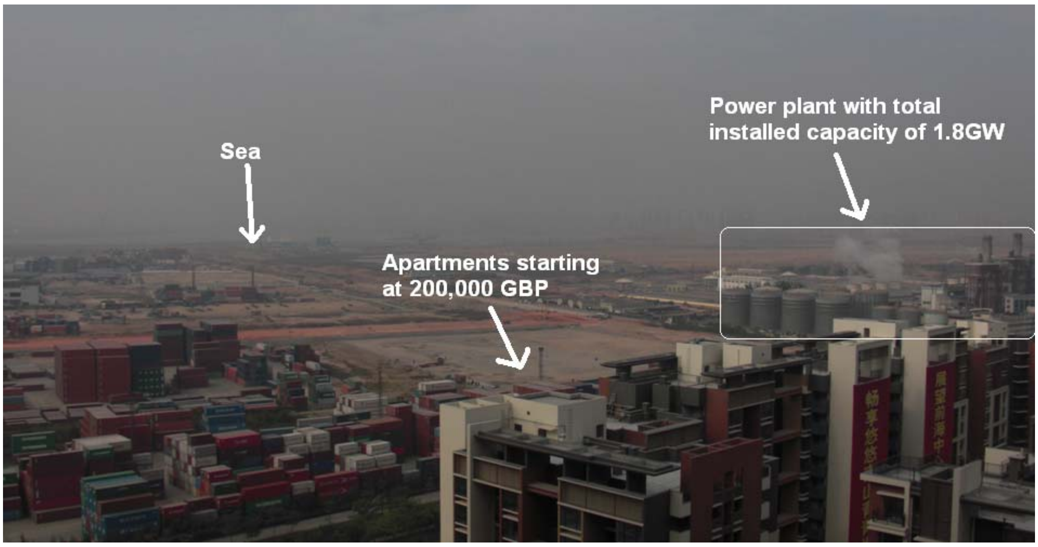

Figure 4-2 View from an apartment close to the Mawan power plant

4.1.3.2 Rural area power plants

1. Coastal or riverside plants

Figure 4-3 is a power plant located in Zhangzhou, Fujian Province, which is originally built with 6×600MW unit next to the sea. The extension project of the power plant has added another 600MW unit at the site. This power plant is currently the second largest power plant in China.

Figure 4-4 clearly illustrates the layout of the generation unit. The unit at the left is the new built 600MW unit, which has its own stack. For the other 600MW units, three units share a common stack, but each of them has its own flue gas ductwork and sea water FGD (Flue Gas Desulphurisation) treatment equipment. The space around the FGD unit and the stack appears limited to accommodate the capture units for the older plant. However, the space around the new built unit is significant. The capture unit could probably be added to the left of the new 600MW unit and without significant changes to the existing plant layout. One of the biggest distinguishing features of this plant is that the coal is stored under the dome shaped roofs rather than on the open ground, in order to reduce the environmental impact to local residents.

Figure 4-3 Houshi Power Plant

Figure 4-4 Details of the generation units

Water for cooling is supplied from a river which is located 50km away from the site, with a pipeline diameter of 1 metre diameter (Huayang 2006).

2. Plants using cooling towers

Figure 4-5 Power plant design layout of the Tuoketuo Power plant (TKT 2008)

The Inner Mongulia Tuoketuo power plant is the world's largest coal-fired power plant in terms of installed capacity. It has 8×600MW installed units as shown in Figure 4-5. The Google image in Figure 4-6 shows the power plant status after the first two units finished construction. The surrounding area is mainly open land without an obvious water supply. Water was supplied from the Yellow River through the "Southern water supply to the North" project. For Units 1 and 2 the water consumption rate is 1.2m^3/s (TKT 2002), which is equal to 4320 t/h. Because the plant is not located in an acid rain controlled area, the requirement for having the power plant built with FGD does not apply to the Tuoketuo Power Plant.

Figure 4-6 Google image of Tuketuo Power Plant (first two units completed, adjacent unit under construction)

New power plants in Inner Mongolia must now also install air cooling systems, which is 30-40% more expensive than the corresponding water cooling equipment. For example, the initial capital investment for Datong 2nd PC 2*600MW plant is 4.8 billion CNY, the cost for the air cooling is 370 million CNY, 7.7% of the total investment (Baidu 2009, Chinahightech 2009). However, no plants in the study up to

2006 appear to have air cooling. However, some of the plants that have cooling towers will be in areas that have water restriction and it might not be possible to increase the water supply if capture is added to it. A detailed analysis is beyond the scope of the study, but a likely solution to this problem is to reject the additional heat from the capture process through dry cooling towers. These will increase the energy penalty for capture by a moderate amount due to the fan power for these towers. Power plants that are built with air cooling are not considered, as most plants that have been investigated in the study have wet cooling. In a water restricted area, even if FGD and wet cooling towers are already in place, then dry cooling towers might still be needed for a capture retrofit since less water per kWh will be lost from them.

Figure 4-7 Detail layout of Tuoketuo Power plant

The extra space to retrofit capture units is limited, as shown in Figure 4-7, especially between each generation unit. However, at the side of the power plants, the space is probably sufficient. If only the generation units at the end of the row (i.e. two out of eight) are required to capture carbon dioxide in the future, the retrofitting cost is relatively cheap compared with retrofitting all the units. Moving the flue gas a longer distance is not impossible, it will only be more costly because of the length of the pipeline and other equipment that is associated with it, such as fans and valves. Moreover, as the flue gas is corrosive, regular maintenance is required for the connecting pipes, this is more difficult and time consuming for the longer pipe. Another issue which will be discussed in section 6.1 is that Chinese power plants are normally built in a way that most equipment of the same purpose will be grouped closely together. Hence, having some separate units might not be acceptable to some plant operators; this is also shown in section 7.

4.1.3.3 Summary of results

Table 4-2 Retrofitting possibility (regarding plant sites)

19%	• Power plants have very high potential to be retrofitted in the future. • Total retrofitting cost is relatively low. • Should be considered as the most easy option for retrofit.
35%	• Power plants have uncertain retrofitting possibility. • Detail engineering assessment work need to be carried out to assess the potential. • Retrofit may only be considered only after the power plants with the easiest options to be retrofitted have been retrofitted.
46%	• Power plants that are most likely to be carbon lock-in in the future. • Should not be considered as an obvious retrofitting option. • If carbon capture becomes mandatory, the cheaper option might be to close the existing plant and built a new power plant.

For the power plants that have been examined three types of retrofitting potential have been summarised in Table 4-2. Only 19% (by number of sites) of the power plants analysed in this study appear to have a high retrofitting potential. The power plants that appear to be at risk of carbon lock-in because of space limitation account for 46% of the 34 out of 74 investigated. Although some of them might still have the possibility to be retrofitted, it is possible that the costs will be significantly elevated. Compared with the fuel saving for advanced new boiler, it might be cheaper to build a new plant at a more appropriate site. The percentages shown in the table are calculated by sites rather than installed capacity. Because the older sites tend to have more smaller size units, the percentage of power plants on sites that are not suitable for retrofit in will be less than 46% in terms of total installed capacity..

For power plants that have an uncertain scope for retrofitting, it is recommended referring to the "capture ready" checklist described in Chapter 5. Differences between the plant condition and the ideal design could then be identified and used for the engineering assessment. Because of the limitation of the present study the current retrofitting potential might be higher than estimated

4.1.4 Future studies

Future work is suggested to be carried out primarily on the more modern large scale power plants. As most of the new large scale plants have been built between 2003 and 2009, Google Earth images might also have been updated during this period. However, unless there are actual policy plans for retrofitting existing power plants into carbon capture plants it is not recommended to carry out such study in depth, as collecting Google Earth image is very time consuming and the plant surrounding area might change greatly during the time of the survey and the time the retrofit happened. At a less rigorous level, a better understanding of the total emission reduction that can be achieved by CCS retrofit technology would be available by doing such a study. An up-to-date detailed plant location survey is also a valuable resource for pipeline route planning and updates should be carried out continuously for pipeline route planning for source and sink matching purposes at regional level. It would be feasible to update annually as new power plant data become available from CEC. Finding updated Google Earth images for existing power plants where the existing latitude and longitude are already know is also relatively straight forward, but it is relatively difficult to locate the new plants.

4.2 Current capture retrofit projects

Table 4-3 Capture retrofit projects in China (CR 2010)

Project Name	Location	Capture capacity (t/y)	Solvent	Started operation	Plant owner
Gaobeidian	Beijing	3,000	MEA	Mid 2008	Huaneng
Shuanghuai	Chongqing	10,000	MEA	2010/Jan	Zhongdiantou
Shidongkou	Shanghai	100,000	MEA	2009/Dec	Huaneng

Three coal-fired power plants CO_2 capture retrofit projects have finished construction in China by the end of 2009 (see Table 4-3), at the time of writing, one plant has been fully operation since mid 2008, the other two are at the test phase. Table 4-3 shows the current retrofit projects in China.

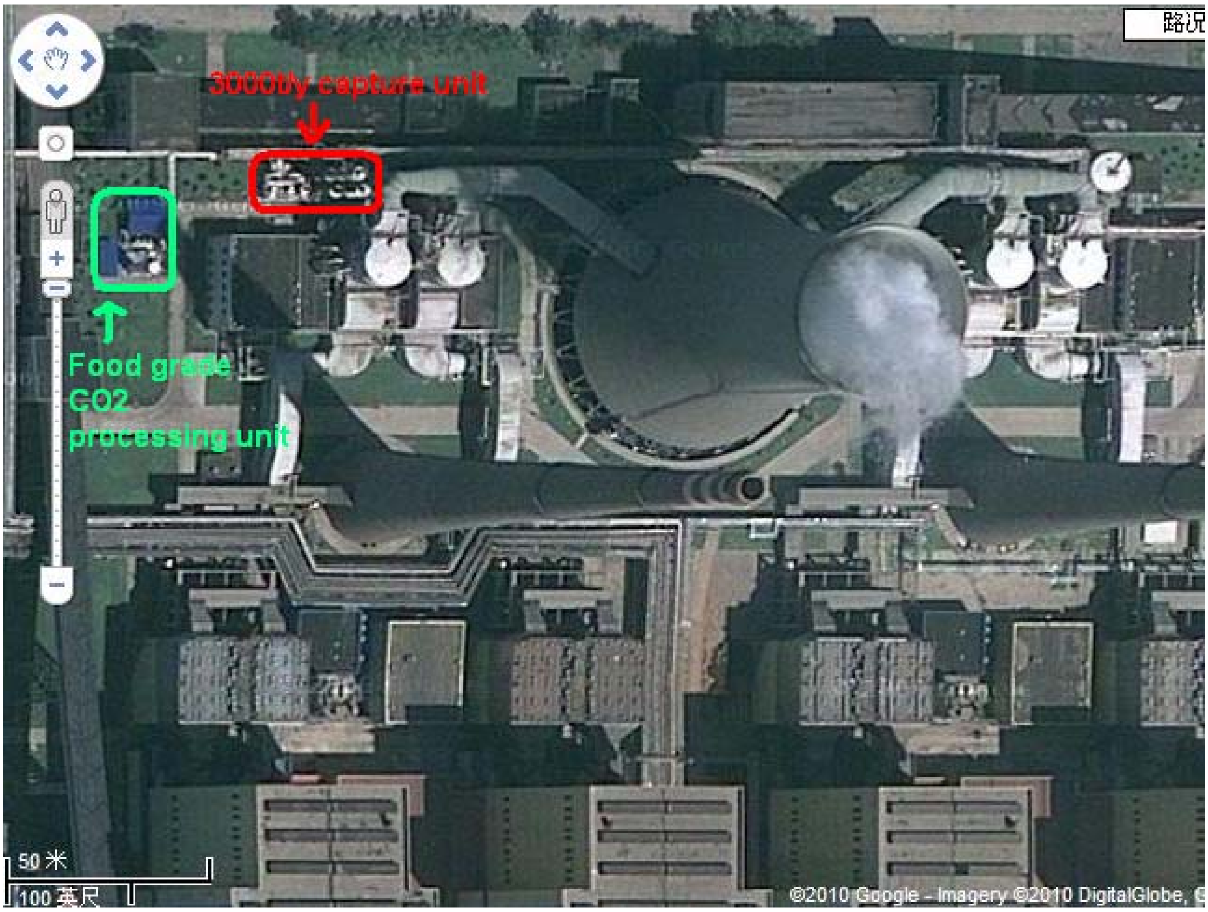

Figure 4-8 Beijing Gaobeidian retrofit units

The Gaobeidian (Figure 4-8) project in Beijing has captured over 3,500 tonne of carbon dioxide since the capture unit started operation in mid 2008, although the total amount of carbon dioxide it has captured is less than 0.5% of that in the flue gas coming out from the power plant. The capture unit is to the west of the cooling tower, which is highlighted in red in Figure 4-8. Carbon dioxide is purified to over 99% at this stage before it is sent to the next purification stage, which is highlighted in green, for further purification to give food grade CO_2. The absorber and desorber of the primary capture unit are both roughly 1 metre in diameter and 4 metres in height. The food grade capture unit is smaller in size but the equipment is manufactured to a higher standard.

Figure 4-9 Shanghai Shidongkou retrofit unit(This figure shows the unit while it is still under construction)

Because the Shanghai plant is relatively new compared with the Beijing plant, the capture unit and the power plant had not finished construction when the Google image was taken. Figure 4-9 shows the location of the 100,000t/y primary capture unit (in red) and the secondary food grade capture unit (in green) at Shidongkou power plant. The total size is roughly half of a football ground. The flue gas handling capacity is equal to 4% of the 660MW boiler flue gas. If more carbon dioxide needs to be captured in the future, the space restrictions will be a problem if it is required to retrofit all the units (currently 2*600MW plus 2*660MW).

Figure 4-10 US Conesville proposed retrofit unit

Other retrofit studies include the US Conesville unit 5 (NETL 2007), which examined retrofitting the 453MW subcritical unit with either oxyfuel combustion or MEA/MDEA scrubbing. The Google image for the MEA retrofitting option is shown in Figure 4-10. An additional SO_2 absorber, which is located next to the stack, is installed to reduce the SOx emission in order to reduce MEA consumption. The two CO_2 absorbers will be installed next to the SO_2 absorber. The CO_2 stripper is located next to the additional letdown turbine at the other side of the generation unit and the compression and gas drying block is located on the site of what was originally the power plant car park. The main difference between the Huaneng design and the Conesville study is that the absorber and stripper are built close together for the Huanneng design, where the Conesville study has a remote stripper and compressor and the Conseville plant is built at a much larger scale. However, if full scale carbon capture is required in China, the overall capture unit without the compression unit will take up almost the same space as the boiler and turbine house.

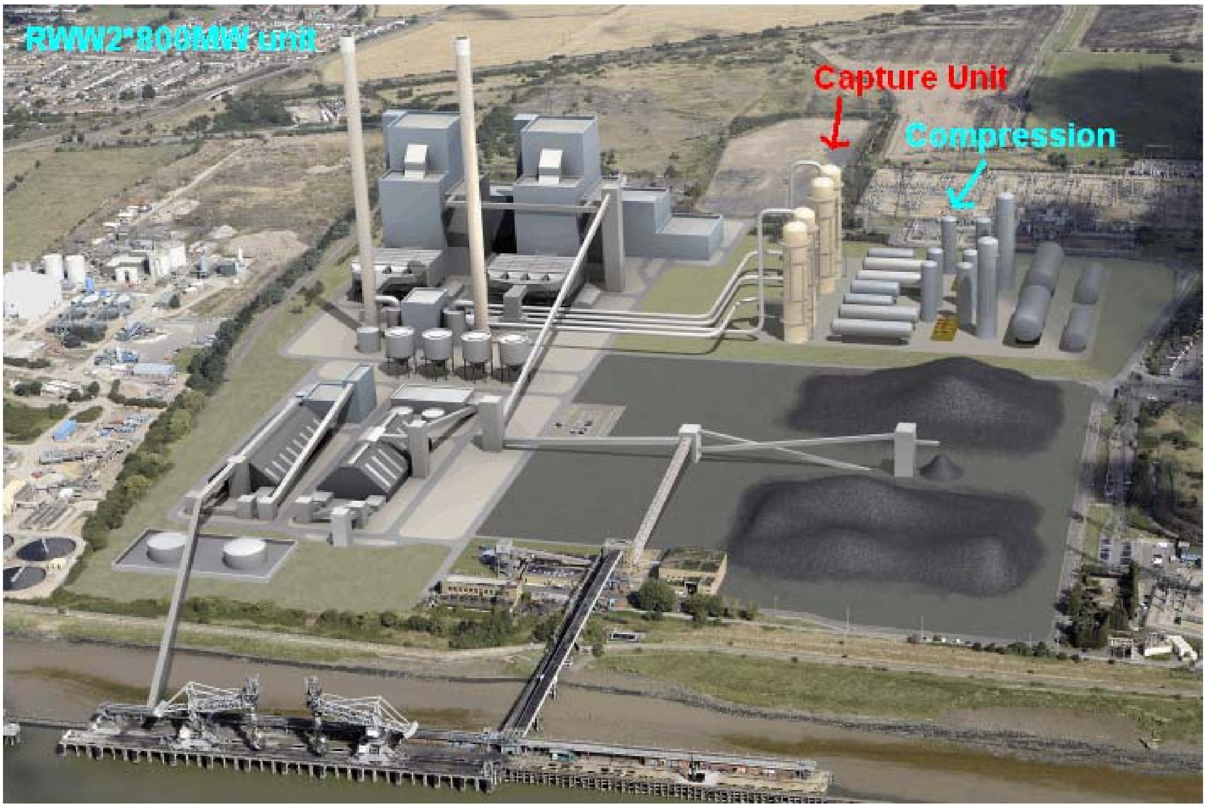

Figure 4-11 RWE Tilbury photo montage (Hotchkiss 2007)

A similar result can be found at RWE's Tilbury plant Figure 4-11 retrofit plan (Hotchkiss 2007). Although the compression unit could be located at further distance away from the stack, the absorber should stay as close as possible to the stack. Because the wet flue gas discharge from the FGD in a wet scrubbing system still contains dissolved chlorides, SO2 and SO3, all of which are corrosive to pipeline. If the pipeline is too long and the flue gas temperature drops, it might accelerate the corrosion speed and result a higher maintain cost.

Another issue that need to be noted is that the results from the survey in this thesis have suggested that the capture unit is likely to be outsourced to a chemical company or be an independent part of the power plant. Therefore, if all capture units are built close together it will be easier to manage. Details of this will be discussed in the survey chapter.

4.3 Retrofit equipments

In this section, the possible retrofit equipment that might be needed for post combustion capture is discussed. Other parallel studies (Hotchkiss 2007; NETL 2007) and projects (CR 2010), have also shown similar inventories based on real case analysis. However, as boiler manufacture and air separation technology improves in the future, oxyfuel combustion should be considered as a potential retrofit option for China.

Table 4-4 Essential capture units for a retrofit plant

Equipment	Function	Indicative operating pressure （Atm）	Indicative operating temperature (^{o}C)
Liquid pump 1	Pump solvent	2-5	40 - 60
Fan/compressor	Flue gas compressor	2-5	40 -70
Liquid pump 2	Lean amine cycle	1.2 - 4	40 - 60
Absorber	CO_2 absorption	1	40 - 60
Stripper	CO_2 regeneration	1.1-2	90 - 120
Heat exchanger	Exchange Heat	1.6 -4	80 - 110
Compressors	CO_2 compression after capture	20 - 50	100 - 150
Cooling column	Cooling the CO_2	20 - 50	20 -40
Splitter	Water separation after CO_2 capture	10 - 20	20 - 40
Mixer	Solvent production	1 - 3	40 - 60
Contact cooler	Adjust temperature for absorption	2 - 5	40 - 60
Reboiler	Reheat amine	1 - 2	300 - 350

The essential capture units which are needed for the retrofit projects are shown in Table 4-4. Absorbers and strippers are key equipment for the capture plant; if food grade CO_2 is required an additional purification unit will also be needed.

4.4 Summary

The current power plant layout research in this chapter has suggested a high risk of carbon lock in if no further action is going to take place. Although 1/5 of the power plants still have a high potential to be retrofitted, the impact of having other plants that might face a shut down decision will not only be a waste in investment but also a threat for climate change. The importance of retrofitting as much plant as possible should be raised in energy policy discussions and the difficulties should also be addressed. The potential barriers for retrofitting existing power plants in China include many issues in addition to space and access to install capture equipment on site. The most important ones are: access to a CO_2 storage site and water consumption related to available water supply. Although detailed examination of these factors is beyond the scope of this thesis (and would be suitable topics for follow-on work) the principal considerations are as follows.

4.4.1 Access to storage site

The suggested maximum distance to a storage site is 300km from the emission site in the IPCC special report on CCS (2005). This is, however, only a guideline distance as in a real case the cost of pipeline for different areas will change and this will change the viable distance. Also, pipelines built in highly populated areas need to have a much thicker wall, so the cost for even a short distance can be higher than the rural are pipeline (Texas 2000). Also, acquiring land for a pipeline will cost money in populated areas.

4.4.2 Space on site

From the clear Google images, rural area plants seem to have a better prospect of having enough space to locate the capture units for the whole power plant. However, some of the plants are built in a compact way that could make it difficult to fit in all of the capture units that would be required. But for most plants, there is the potential to have at least partial retrofit, which means retrofitting only some of the generating units rather than the whole power plant. Although power plants in China are normally built alongside each other, at each end of the line of generating units the space is normally big enough to accommodate a smaller scale capture unit. However, the plants in the more developed areas have less free space around the units and should be considered to have the least potential to be retrofitted in the future.

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Chapter 5 Carbon capture modelling for existing pulverized power plants

In order to demonstrate a simple way of preparing to retrofit a pulverized power plant through computer modelling, an example simulation for a capture retrofit using ASPEN Plus (Advanced System for Process Engineering, ASPEN thereafter) to simulate the complete system comprising the PC plant and the capture unit is shown in Appendix 2. However, the software has no standard sub-module for a boiler so similar modules are selected. The methodology for using ASPEN in this application is listed in Figure 5-1:

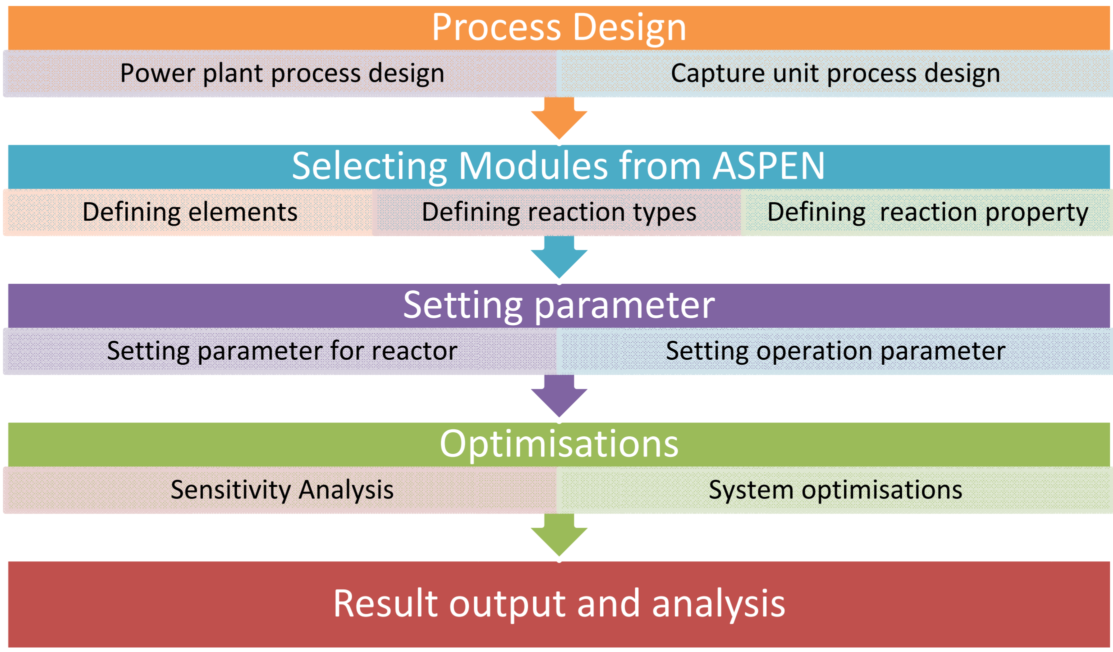

Figure 5-1 Procedures for using ASPEN for carbon retrofit analysis

First of all, a 1GW power plant is selected as the base load plant and the post combustion capture process is also added to the plant accordingly. Secondly, corresponding ASPEN simulation modules are chosen from ASPEN. The parameters for individual components will be set based on the power plant operating conditions. The software is then ready to be run and the result will be used for comparison. In this case, steam for the capture unit will be extracted from two different points. The one with a lower efficiency penalty will be set as the default system and used as the final model.

5.1 Process design

The process design includes two parts: conventional power plant process design and capture unit process design. In this simulation, a 1000MW unit at the Zhouxian Power Plant in Shangdong, China is selected and a monoethanolamine (MEA) based solvent is selected for system modelling. The aim of this modelling is not to identify the best possible capture option for Zhouxian, but to demonstrate how a relatively simple model can be used to investigate the effect of changing various parameters. Based on the example results presented, possible suggestions for minor plant modification are given, that might increase the potential market for carbon capture in China.

5.1.1 Base load power plant selection

Under the policy of increased energy efficiency and reduced coal consumption for each kWh of electricity generated, one of the most advanced 1000MW units is selected as the base line plant, as it is facing less uncertainty of being shut down in the future. This representative advanced power plant is selected as the model to demonstrate the analysis process. Harbin Boiler, Dongfang Boiler and Shanghai Electricity are the biggest three boiler and turbine companies in China. In 2006, the combined market share of the three boiler companies accounted for 75% of the total installed capacity in China and their market share for the steam turbine businesses accounted for 85% of the total capacity (SE 2009).

Figure 5-2 and Figure 5-3 indicate the detailed boiler orders to the end of 2009 for Dongfang Boiler and Harbin Boiler. The column in orange represents the total orders for a particular type of boiler, and the green column standing next to it represents the boilers already shipped to the power plants. It can be seen that both of the boiler companies do not have any outstanding orders for 600MW subcritical boilers and that the 1000MW ultra supercritical boiler has the highest order to operating ratio. The demand for a higher capacity and higher steam temperatures and pressures is clearly indicated in these tables.

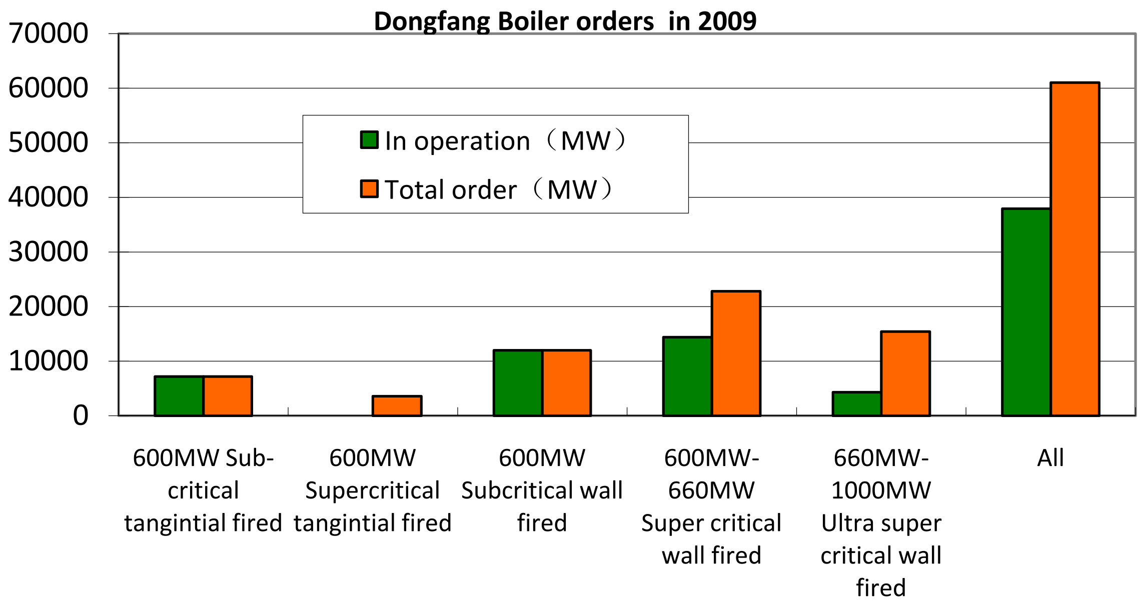

Figure 5-2 Dongfang Boiler orders in 2009 (Linkschina 2009)

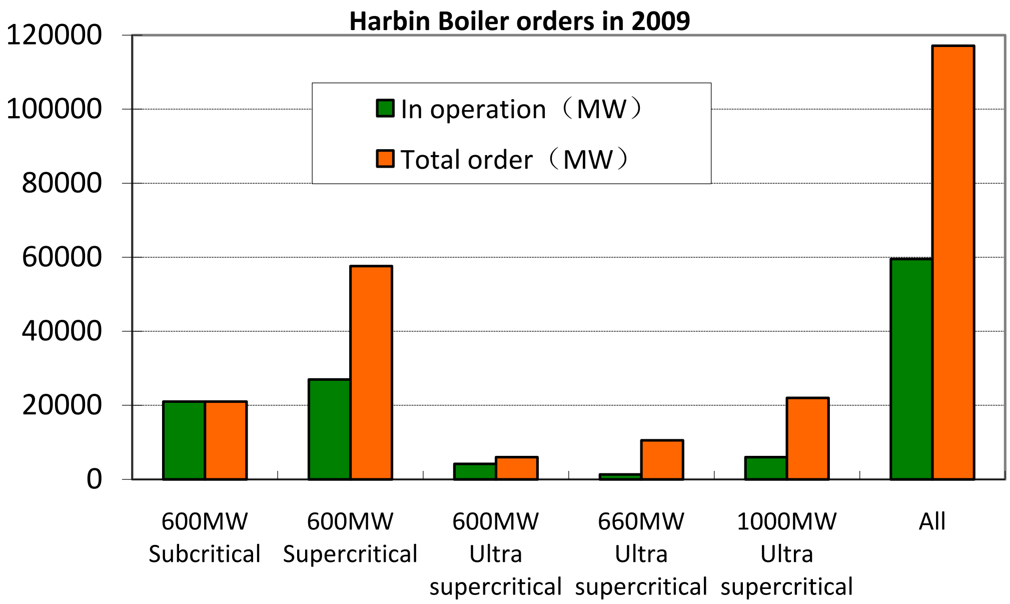

Figure 5-3 Harbin Boiler orders in 2009 (Linkschina 2009)

Table 5-1 1000MW Boiler orders for Dongfang and Harbin Boiler (Linkschina 2009)

Operation	Location	Plant owner	Installed capacity	Boiler Type[15]
01/12/2006 01/07/2007	Zhouxian, Shandong	Huadian	1000MW*2	DG3033/26.25-II1，Bit.
01/06/2009	NingBo, Zhejiang	Guandian	1000MW	DG2996/27.56-II1，Bit.
01/02/2008			1000MW	
	Shantou,Guangdong	Huaneng	1036MW*2	DG3033/26.25-II1，Bit.
	HoluDao, Liaoning	Shenhua & Guohua	1000MW*2	DG3033/26.25-II1，Bit.
	Laizhou, Shandong	Huadian	1039MW*2	DG3033/26.25-II1，Bit.
01/11/2006 01/12/2006	Taizhou, Zhejiang	Huaneng	1000MW*2	HG-2950／27.56-YM，Bit.
01/04/2007 01/11/2007			1000MW*2	
01/12/2007 01/03/2008	Taizhou, Jiangsu	Guodian	1000MW*2	HG-2980／26.15-YM，Bit.
2008/12	Chaozhou, Guangdong	Datang	1000MW*2	HG-3110／26.25-YM，Bit.
	Wuhu, Anhui	Huadian	1000MW*2	HG-3033／26.15-YM，Bit.
	Jinzhou, Shanxi	Datang	1000MW*2	HG-3375／26.25-YM，Bit.
	Chifeng, Inner Mongulia	Datang	1000MW*2	HG-3313/26.15--HM，Brown
	Nanjing, Jiangsu	Huaneng	1000MW*2	HG-3100／27.56-YM，Bit.
	Wenzhou, Zhejiang	Huarun	1000MW*2	HG-3033／26.15-YM，Bit.
	Tangshan, Hebei	Huarun	1000MW*2	HG-3100／26.15-YM，Bit.
	Zhumadian, Henan	Huarun	1000MW*2	HG-3100／26.15-YM，Bit.

[15] DG: Dongfang boiler; HG:Harbin boiler, DG3033/26.15-II1 means manufactured by Dongfang Boiler, the main steam flow rate is 3033t/h and the steam pressure is 26.15 MPa

Table 5-1 indicates the 1000MW boiler orders for Dongfang Boiler (DG) and Harbin Boiler (HG). The highlighted green entries are boilers that are already in operation; others are still at the manufacturing stage. In contrast to other major electricity markets around the world, the market for 800MW boilers almost does not exist in China. The reasons for that are not explored in this study, but a result of the market being absent for the 800MW units is to provide a much simpler calculation environment for capture ready and retrofit designs. Thus when only 1000MW and 600MW power plants make up the market, the flue gas can be calculated as just two different emission scenarios and other associated equipment will be more easy to manufacture on a large scale.

Capture ready design should also start with the plant types that are most likely to dominate the market in future, which are plants with 1000MW ultra super critical and with 660MW ultra super critical boilers. Both types of boiler operate at 26.15-26.25MPa and mostly burn bituminous coal. Also, most of the new plants are located along the Eastern coastline or at coal mines. Therefore, in the capture retrofit modelling, the 1000MW boiler unit at Zhouxian is selected as the baseline plant for the study. Another 6 units with 6GW in installed capacity having a similar design will start operation in two to three years time, as can be seen from the boiler order table.

5.1.2 Capture unit selection for primary study

Monoethanol amine (MEA), methyl diethanol amine (MDEA), methyl diethanol amine DEA are three commonly-studied types of amine solvents (Kohl and Nielson 1997; Jing, Dong . 1999; Aroonwilas, Chakma et al. 2003; Ali 2006). Due to the availability of chemical data, MEA was chosen in this simulation; it is also widely considered to have the fastest reaction rate and thus to be most suitable for flue gas absorption at the moment. However, the energy consumption needed for regeneration is high and uninhibited MEA solutions cause corrosion to carbon steel equipment (Kohl and Nielson 1997; Jing, Dong 1999; Tan 2005). This study has taken into account aspects of real plant operating conditions and SOx and NOx are included in the model.

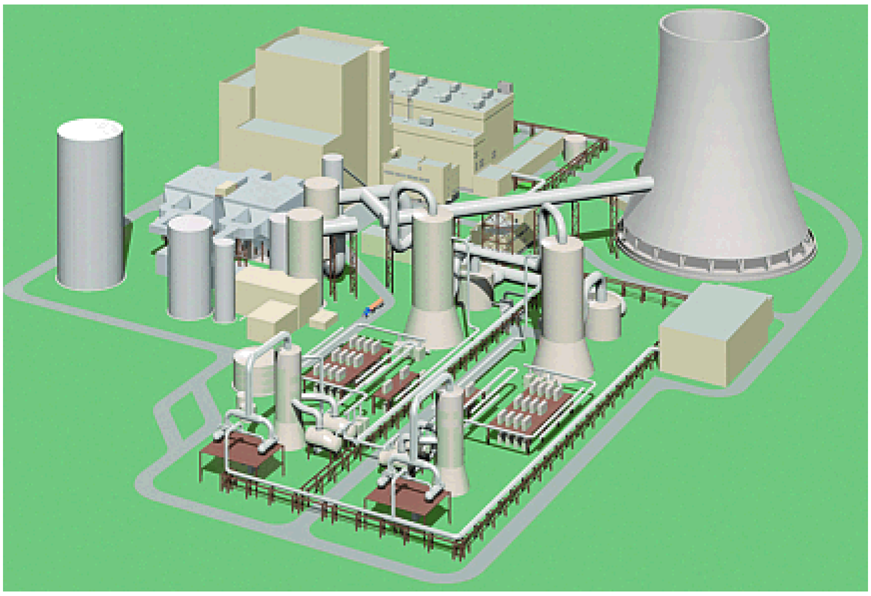

Figure 5-4 Post combustion capture for pulverised power plants (Siemens 2009) – note how the clean flue gases after CO_2 removal are vented into the cooling tower to give plume buoyancy without additional heating and to dilute the inert gases with the cooling air flow.

Table 5-2 Environmental targets for pulverised coal plants in China, based on (DB31/ 387—2007**)** (Gibbins, Lucquiu et al. 2008)

Pollutant	Environmental Target	Possible Control Technology
Particulates	50 mg/Nm^3 (A)	Electrostatic Precipitator (ESP) or Bag-type dust remover
SO_X	400 mg/Nm^3 (A)	Wet limestone scrubber
NO_X	V_{daf}<10%, 1100mg/Nm^3; 10%≤V_{daf}≤20%, 650 mg/Nm^3; V_{daf}>20%, 450 mg/Nm^3 (A)	Low NO_X burners, overfire air and SCR or SNCR

Figure 5-4 shows where the carbon capture units would be added to a conventional power plant. The power plant can be considered as two main parts: the water-steam cycle and the coal-flue gas chain. The coal burnt in the furnace will raise superheated steam from the water that goes into the boiler. Flue gas exiting the boiler will then go through various cleaning stages. The first clean-up stage for the flue gas is normally NOx removal, followed by particulate removal and then SOx removal; pollutant levels should be lower than listed in Table 5-2. With capture retrofit, the capture unit is added as a final stage before the flue gases are vented to atmosphere.

5.1.3 Parameters of Zhouxian 2×1000MW power plant

The methodology for selecting the power plants involves finding a popular plant configuration that is likely to be built more in the future, then obtaining the operating data for one of the real plants of that type, inputting that into the model and adjust the running condition to make it suitable for capture.

Zhouxian Power Plant is located at Zhouxian, Shandong Provinces. The first 1000MW started operating in 2006 and the second unit started operating in 2007. It was the second power plant to have 1000MW units in China. The successful operation of these advanced plants has resulted in another 8 units being built in China's four main power companies. Due to new regulations on power plants, single unit capacity should be limited to no more than two different unit sizes at a power plant, as will be discussed in Chapter 5. This means that when a power company needs more generation units, and it already accommodates two different types of unit, then it will need to start a new company to host the additional unit. This policy has affected the Zhouxian power company and forced it to split into two companies. In 2008, the original Zhouxian power plant was divided into two entities, Zhouxian Power Plant which owns the old 2×600MW and 4×335MW units and Zhouxian Power Company Ltd (Zhouxian thereafter) which owns the 2×1000MW units. The design parameters for the supercritical boiler in this study are supplied in Table 5-3 and the design parameters for the steam turbine are shown in Table 5-4.

Table 5-3 Technical parameters of the 1000 MW boiler (NEDI and SEI 2003)

Boiler type	DG3000/26.15-II-1[16]		
Design capacity	1000MW		
Parameter	Unit	BMCR[17]	BRL[18]
Coal flow rate	t/h	413	429
Main steam flow rate	t/h	3033	2889
Main steam pressure	MPa(a)	26.25	26.11
Main steam temperature	^oC	605	605
Reheater steam flow rate	t/h	2469.7	2347.1
Reheater inlet steam pressure	MPa(a)	5.1	4.841
Reheater outlet steam pressure	MPa(a)	4.9	4.641
Reheat steam inlet temperature	^oC	354.2	347.8
Reheat steam outlet temperature	^oC	603	603
Economizer outlet steam temperature	^oC	302.4	298.5

Table 5-4 Technical parameters of 1000MW steam turbine (NEDI and SEI 2003)

Turbine type	**D1000A-1～2t[19]**
Turbine rated load：	≥900 MW
Turbine maximum continuous rating (TMCR)	1000 MW
Steam pressure at main steam valve inlet：	25 MPa(A)
Steam temperature at main steam valve inlet	600℃
Steam temperature at reheat steam valve inlet	600℃
Average condenser pressure	11.8kPa(A)
Guaranteed heat rate based on Turbine heat acceptance (THA) condition	7450 kJ/kWh

16 DG: Dongfang boiler type II design one with main steam flow of 3000 tonne/hr, main steam pressure of 26.15MPa

17 BMCR: Boiler maximum continuous rating

18 BRL: Boiler rated load

19 Dongfang turbine with 1000MW output type A

The properties for the design coal and the check coal, different blends of Yankuang and Jibei coals, are shown in Appendix 2A.

5.1.4 ASPEN process flow diagram for Zhouxian power plant

The whole process of carbon capture for a unit at Zhouxian Power Plant is shown in Figure 5-5. The integrated PFD comprises the coal combustion unit, power generation unit, denox unit, FGD unit and CO_2 capture unit. In the process of building the entire model, separate units were built individually before combining into a whole package. The details of the module development process are given in Appendix 2B. In this model, the power plant is expected to run at its boiler maximum continuous rating (BMCR). This is because after adding the carbon capture unit, electricity production is expected to decrease. In order to maintain the same amount of electricity output, the boiler should operate at its highest rate.

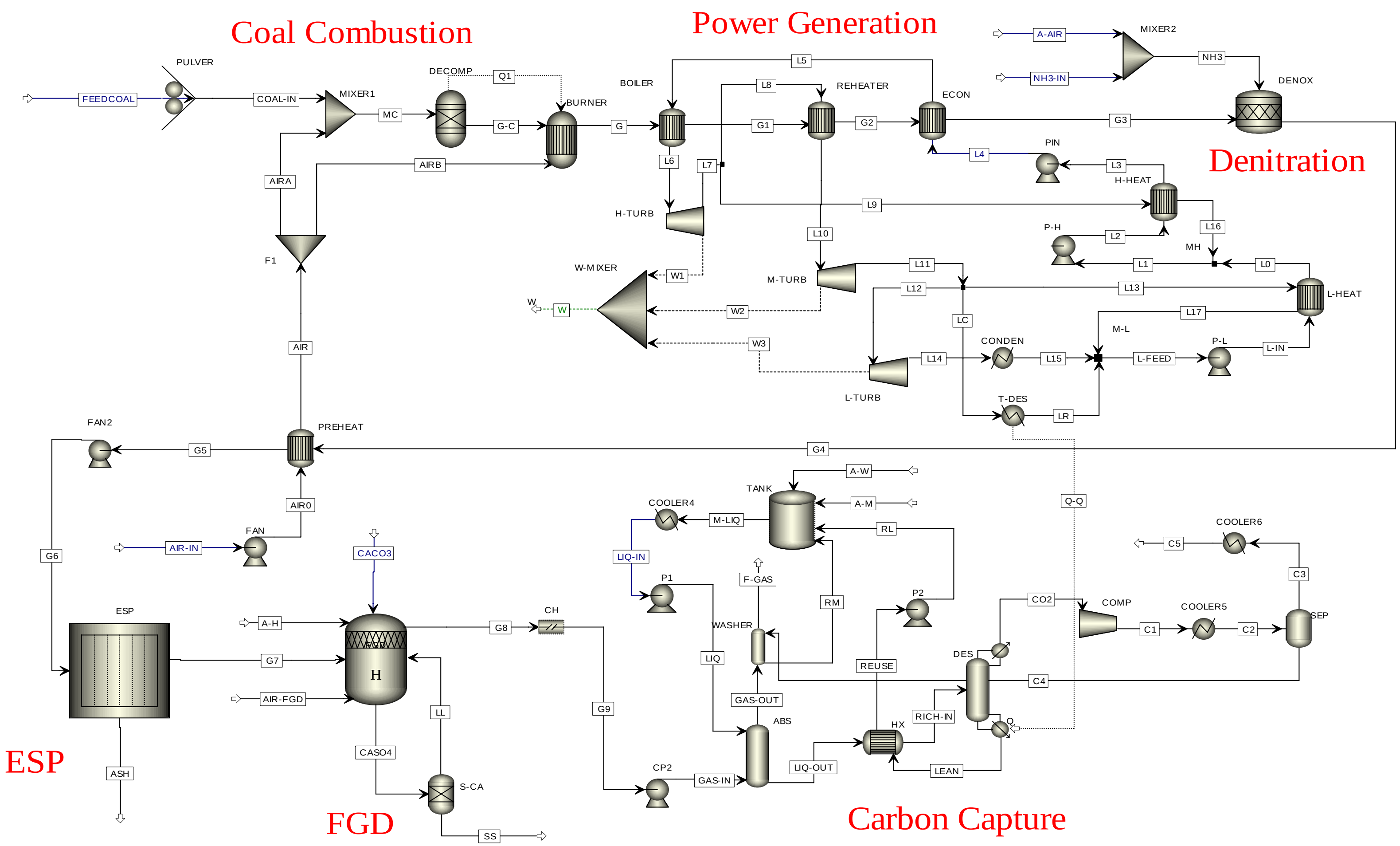

Figure 5-5 Process Flow Diagram (PFD) of Zhouxian carbon capture plant

5.2 Module selection and parameter settings

5.2.1 Coal combustion unit

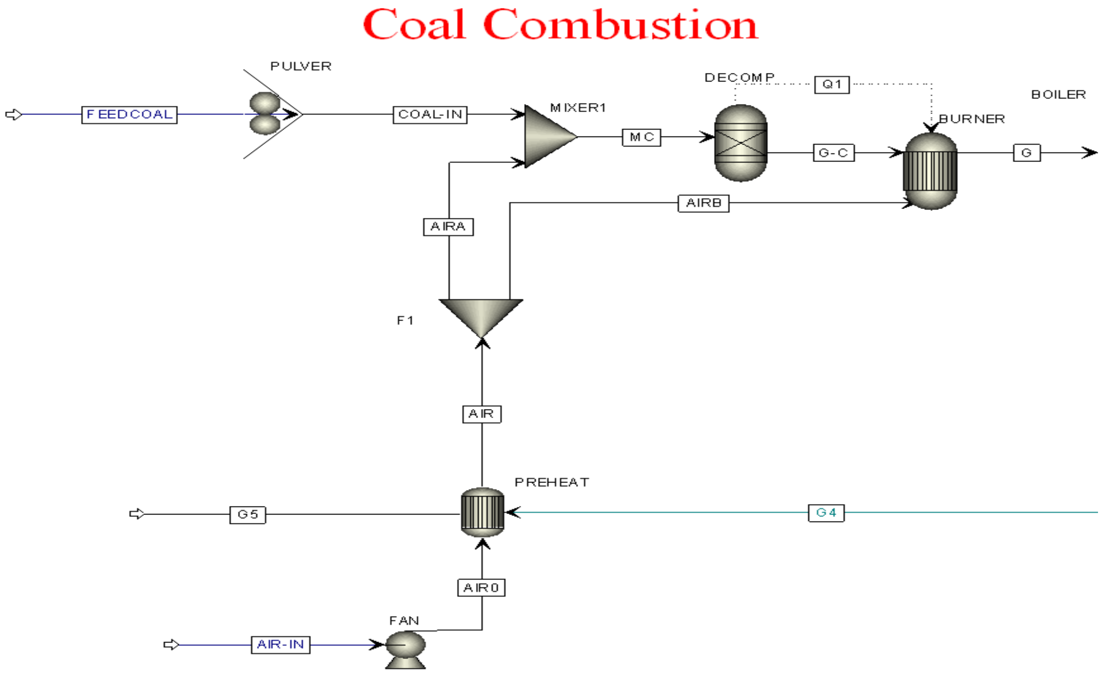

Figure 5-6 PFD of coal combustion

The process flow diagram (PFD) for the coal combustion unit is shown in Figure 5-6. In a conventional power plant, coal supplied as raw material needs to pass through two processes (usually combined) before going into the boiler, coal pulverising and drying. After the FEEDCOAL passes through the pulverising mill (PULVER), it will be dried by AIRA from the air preheater (PREHEAT) then goes into the DECOMP reactor, the moisture is separated from coal and enters the BURNER in the modelling. Hot air exiting from the deNOx unit will heat up the AIR-In before react with the coal.

According to ASPEN(2002), RKS-BM was chosen as physical property for the coal combustion unit, as this is suitable for gas processing, refinery and petrochemical applications. Although ASPEN is not built for coal combustion simulation, this process involves a lot of high pressure gas reaction. IDEAL was chosen as physical property of low pressure solid and gas for the PULVER and PREHEAT. Due to the complicated design inside a boiler, it is separated into several units in this modelling. The superheater, reheater, economizer and air heater are all separate modules located in the coal combustion and power generation units. The modules and their names in the ASPEN model are shown separately in Table 5-5 and Table 5-6.

Table 5-5 Module selection for coal combustion unit

ASPEN module or code	Unit in power plant	Module type
PULVER	Pulveriser	SSplit
MIXER1	Mixer	Mixer
DECOMP	Low temperature zone at burner	RYield
BURNER	Burner inside boiler	RGibbs
F1	Stream separator	SSplit
PREHEAT	Air preheating insider boiler	HeatX
FAN	Fan	Fan

The results of the simulation are shown in Appendix 2B. CO_2 from the flue gas is 13.8%, NOx is 0.2% and SOx is 0.0871%. The input of the coal and flue gas that will be used in the next stage of simulation is highlighted in yellow. The result is consistent with the number provided by the original plant operation handbook. The coal input for the plant is 401tonne/hr and the carbon dioxide is produced at a rate of 704.795 tonne/hr for the 1 GW unit. In this simulation, the heat from G7 is provided by the flue gas after passing the DeNox unit, which is described in 5.2.3.

5.2.2 Power generation unit

The simulation results for flue gas and steam cycle are shown in Appendix 2C and Appendix 2D. The module selection for the power generating unit is shown in Table 5-6. The process flow diagram is shown in Figure 5-7 (with the absent of LC, LR and T-DES). The hot flue gas G from the coal combustion heats up the water in the boiler into high temperature and high pressure steam which then enters the high pressure steam turbine for electricity generation. Hot water enters the H-heater and increases its temperature to over 200^{o}C with a pressure increase to over 23 MPa after passing through the feed pump P-H. The hot and high pressure steam and water mixture goes into the economizer via stream L4. As L4 passes through the economizer, the temperature continues to rise before it enters into the BOILER, which is the superheater inside the boiler. The extremely hot steam will go through stream L6 into the high pressure turbine, release heat and generate electricity. One part of the cooled steam will leave from stream L8 enter the reheater and enter the intermediate and low pressure turbines, where electricity is generated again. The other part will leave from L9 and goes into the H-heat. The medium pressure steam leaving the M-TURB will be separated into 2 streams, L12 and L13, in the normal power generation process. L12 goes into the L-TURB and generate electricity, while L13 goes into L-HEAT for the next steam cycle.

Table 5-6 Module selection for power generating unit

ASPEN module or code	Unit in power plant	Module type
Boiler	Superheater inside boiler	HeatX
Reheater	Reheater inside boiler	HeatX
Econ	Economizer inside boiler	HeatX
H-Turb	High pressure steam turbine	Compr
M-Turb	Intermediate pressure steam turbine	Compr
L-Turb	Low pressure steam turbine	Compr
H-heater, L-Heater	High pressure heater and low pressure heater	HeatX
Conden	Steam condenser	HeatX
COOL	Cooler	HeatX
T-DES[20]	Heat exchanger for solvent	HeatX

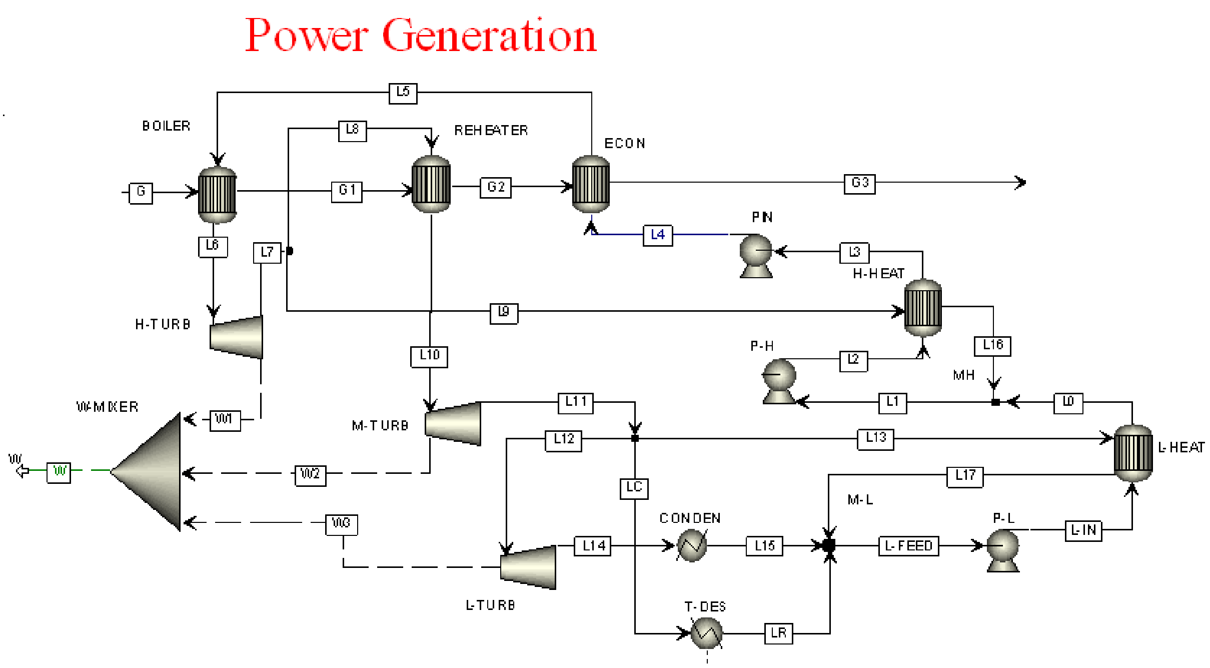

Figure 5-7 PFD of power generation unit

[20] T-DES only exist in the retrofit plant. In the retrofit process, LC is a substream from L13, which provides heat for the desorber.

Electricity is generated through the H-Turb, M-Turb and L-Turb, the total output for the work is 993.8MW electricity from the calculation. When integrating the heat consumption of the capture unit and the turbine, LC can be used to provide the heat for solvent regeneration as shown in Figure 5-7. In this model, LC is set to be 425 tonnes/h in order to provide all the heat for the desorber in the carbon capture unit. Before having the LC stream, the mass flow rate for L13 is 734.5tonnes/h. The changes in the flow have also change the work of the P-L, P-H and PIN pump from 36.3MW to 308.7MW, a 271.9 MW difference in the simulation. Further analysis on the difference in work load for pumps will be discussed in section 5.2.6.

5.2.3 DeNox unit

Selective Non Catalytic Reduction (SNCR), Selective Catalytic Reduction (SCR) and Irradiation by Electron Beam (IEB) are the most popular NOx reduction methods (Gibbins, Lucquiaud et al. 2008). In the Zhouxian plant, a DeNOx unit was not installed at the time when the plant was built, but space and pipeline connections for the unit have been planned and designed between the economizer and air preheater (NEDI and SEI 2003). The flue gas is currently passing through an empty spool piece. The technology proposed in the plant feasibility study is the selective catalytic reduction (SCR) method, which is also the most potentially effective method among the DeNOx technologies. Ammonia and a catalyst are used to reduce NOx, N_2 and H_2O in the SCR process, which is designed for 80% reduction (Gibbins, Lucquiaud et al. 2008). Reactions taken place in the unit are (Chen 2006; Liu 2006):

$$4NO+4NH_3+O_2=4N_2+6H_2O$$

$$2NO_2+4NH_3+O_2=3N_2+6H_2O$$

$$6NO+4NH_3=5N_2+6H_2O$$

$$6NO_2+8NH_3=7N_2+12H_2O$$

$$2SO_2+O_2=2SO_3$$

$$NH_3+SO_3+H_2O=NH_4HSO_4$$

$$2NH_3+SO_3+H_2O=(NH_4)_2SO_4$$

The process flow diagram is shown in Figure 5-8 and the results are shown in Appendix 2E.

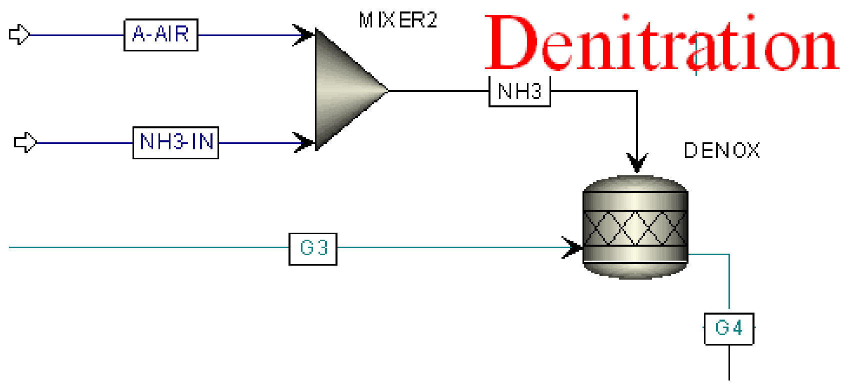

Figure 5-8 PFD of DeNOx unit

Because SO_2 will also react with the ammonia during this process, normally WO_3 and TiO_2 are used as catalysts to limit the amount of the SOx reaction. The national environmental pollution limit for NOx is 450mg/m^3 in China. The plant has already installed low NOx burners and staged overfire air in the boiler for NOx reduction, which is also a popular design among other new advanced boilers. According to the plant feasibility study, the NOx level is designed to be lower than 100 mg/m^3 (at 6%v/v dry O_2), which is around 75% of the original amount. The Rstoic Module is chosen and the RKS-BM method was selected in this model. The model has integrated this part of the heat for air preheating as described in 4.3.1. The NOx level has reduced as expected and is highlighted in yellow in the table.

5.2.4 ESP

The PFD of the ESP is shown in Figure 5-9 and the results are shown in Appendix 2F. It is estimated that ash level has gone down to zero after the ESP unit for the purposes of the simulation. The model selected is the original ESP unit from ASPEN. Ash level goes down to 3.138 tonne/hr, which is 97% less than its original level.

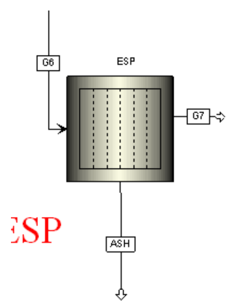

Figure 5-9 PFD of ESP

5.2.5 DeSOx unit

A wet scrubber flue gas desulfurisation (FGD) system was installed at the time the new plant was built. This uses cheap limestone to react with SO_x and form calcium sulphate ($CaSO_4$) or calcium sulphite ($CaSO_3$), the latter being oxidised to sulphate by bubbling air through the slurry later. The main reactions in the system are:

$$2SO_2+2CACO_3+O_2=2CASO_4+2CO_2$$

$$CASO_4+2H_2O=CASO_4\cdot 2H_2O$$

$CaCO_3$ and water are mixed together as the sorbent, with a density of 1.1-1.4×10^3 kg/m^3. SO_2 and oxygen going into the system react with the solvent and form calcium sulphate.

A Mixer and the Flash Module are used to simulate the FGD, and the property is chosen to be ELECNRTL. The process flow diagram is shown in Figure 5-10.

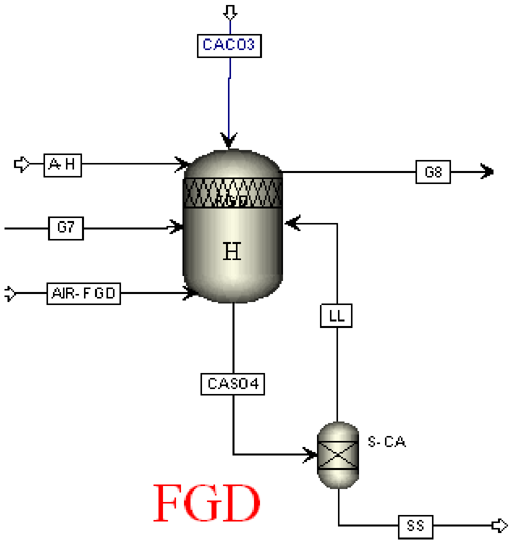

Figure 5-10 PFD of FGD unit

In the feasibility study (NEDI and SEI 2003), the gypsum produced form FGD contains less than 10% of water and the production rate is shown in Appendix 2G. Parameters for the FGD are shown in Appendix 2H.The pollutant emission estimates for the Zhouxian plant are shown in Appendix 2I .

Comparing the result with the simulation (Appendix 2J), the limestone production is 12.2t/h, which is 12% lower than the initial estimation. However, the SO_2 result is similar to that of the original design calculation. The temperature coming out from G7 is around 50°C, which is the design temperature at the FGD exit, but is lower than the 80°C required temperature before going into the stack. Therefore, in reality, it is heated up again before going into the atmosphere in the normal process. If carbon capture becomes mandatory, the capture unit should be located before the flue gas from FGD is heated up.

5.2.6 Carbon capture unit

MDEA and MEA have been used for carbon capture simulation in a large number of studies (IPCC 2005). However, because of the cost and manufacturing issues, MEA is more often used in the capture plant designs, as mentioned above. This model uses MEA as an example for the Zhouxian simulation of a carbon capture retrofit unit installed in the power plant. A similar approach could be used for other amine based solvent, such as MDEA, DEA and TEA. The results from this simulation were compared with results from other studies.

In this model both the absorber and desorber used RadFrac as the module type. Table 5-7 shows the module selection for the carbon capture unit. ELECNRTL is chosen for the physical property. The reaction constant which is need is shown in

Table 5-8.

Table 5-7 Main module selection for carbon capture unit

ASPEN module or code	Unit in power plant	Module type
CP2, P1, P2	Pump	Pump
ABS	Absorber	RadFrac
WASHER	Desorber for MEA	RadFrac
HX	Heat exchanger	HeatX
DES	Desorber	RadFrac
COMP	Compressor	Compr
COOLERS	Cooler	HeatX
SEP	Desorber	RadFrac

Table 5-8 Reaction Constant for MEA (ASPEN 2002)

Reaction	ln(Keq)=A+B/T+C*ln(T)+D*T			
	A	B	C	D
$CO_2 + 2H_2O = H_3O^+ + HCO_3^-$	231.465	-12092.1	-36.7816	-
$HCO_3^- + H_2O = H_3O^+ + CO_3^{-2}$	216.049	-12431.7	-35.4819	-
$2H_2O = H_3O^+ + OH^-$	132.899	-13445.9	-22.4773	-
$MEAH^+ + H_2O = MEA + H_3O^+$	-3.038325	-7008.3569	-	0.003135

$H_2O + MEACOO^- = MEA + HCO_3^-$	-0.52135	-2545.53	-	-

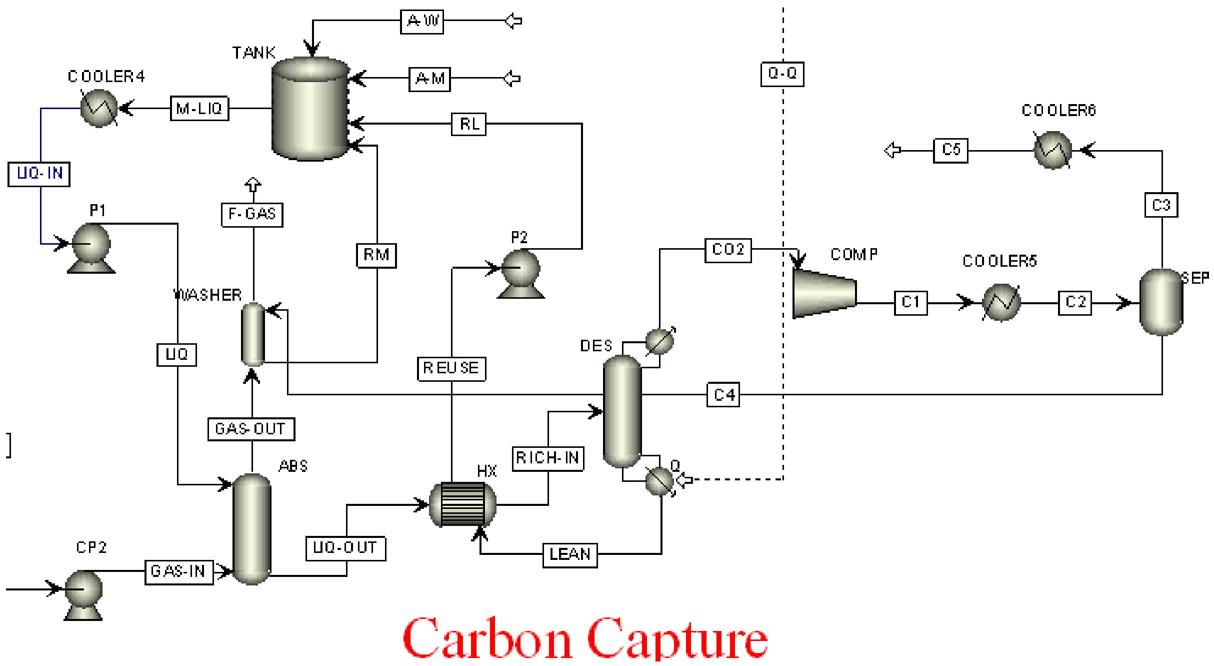

Figure 5-11 PFD for Carbon Capture Unit

The PFD for the capture unit is shown in Figure 5-11. Flue gas coming out from the FGD unit enters the absorber and reacts with the MEA flowing down the column (packing or other details of the reactor are not considered at this stage). The CO_2 rich liquid will leave the absorber and enter the desorber, where CO_2 is separated and the MEA is recycled back to the absorber. Due to the limited chemical experimental data, the consumption rate for MEA is not calculated and it is assumed that the reflux ratio for ASPEN calculations in the simulation is 0.03. When considering the consumption rate, the cost for capture will be higher and the capture performance could be reduced. In this process, the LEAN MEA coming out from the desorber has a higher temperature, which is used for heating up the MEA going into the absorber in the cross flow heat exchanger.

The simulation result is shown in Appendix 2K and Appendix 2L. N_2, CO_2, O_2 and H_2O in mass fraction in the gas inlet stream is 78.8%, 13.8%, 1.3%, 5.0% respectively, and after the gas passes through the 30% MEA solution, the CO_2 will have a 93.9% concentration after drying at stream LIQ-OUT with a carbon dioxide capture rate of 89.9% from the ABS. The flue gas coming out from the top of the ABS (absorber) goes into a WASHER, where MEA carried away by the flue gas is recycled. The CO_2-rich solvent from LIQ-OUT stream exchanges heat with the desorbed MEA in the LEAN stream before going into the DES (desorber). After the CO_2 is separated from the solvent, it will be compressed for transport.

The heat provided for the DES is coming out from steam extracted from the intermediate pressure turbine, and the total amount of heat needed to supply the DES work is equivalent to 425 tonnes/h from stream Q-Q. After exchange heat with the DES, the temperature of stream LC (which supply heat for Q-Q) dropped from 313.2 ^oC to 162.3 ^oC in LR. There was also an increase in the work load for pump and other associated equipment to 271.9MW in the power generation part and the work load for the compression unit is 137.7MW.

The total work output from the power plant before adding the carbon capture unit is 993.8MW. After the capture unit is added, the power plant output changed to 584.2MW (CO_2 compressed to 11MPa) or 721 MW (without compression).

5.3 Optimisation

Under the previous assumption, the specified power consumption per tonne of carbon dioxide is 341.9kW/tonne CO_2. The number is more than twice higher than the IEA GHG (2004) study. The reason being that at the beginning of the modelling work, only minimal adjustments to the turbine were considered, because it is one of the expensive items in a power plant and the total gas flow rate and heat provided is similar to that is needed in the capture unit. But this ignored one factor, which in this case the heat used for the capture plant, would need some from electricity generated from the plant to avoid too much modification for the base power plant. But this is not as efficient as using and the heat from the steam directly without the losses involved in generating electricity.

Hence, a modification on the steam extraction is made to test the power consumption. After steam extracted for LC from L13 which goes into the L-heater (low pressure heater) changed its source to L12 which supply the low pressure turbine, the power consumption rate for capturing the carbon dioxide has changed to 107kW/tonne CO_2. In this scenario, the efficiency change (LHV) is 8.6% for a 90% capture level, and the carbon dioxide captured is 852.3 g/kWh. The modification could be achieved by having a new turbine configurationin order to achieve the best efficiency (IEA, 2007), or by modifying the existing turbines. The final result is similar to the IEA GHG (2004) study. While in this study, power plant is assumed to be operating at its maximum boiler continues flow rate (MBCF), which is slightly higher than 100% load factor. As the information for power plant operating under MBCF has the most comprehensive design data, and it is easy for comparing results in ASPEN. As mentioned in chapter 3, the current average load factor in China is only around 50%. But, if we use the current projected increased capacity for new built power plant within the next 20 years and growth in the electricity generated use the load factor needs to be increased; Hence the MBCF is used in the simulation and it is assumed that CCS plants will be operated at full load.

Table 5-9 Comparison of 50% and 90% capture

Post-combustion capture on advanced supercritical pulverized coal plant	Steam extracted from L12 (low pressure turbine)	MEA 90% capture			MEA 50% capture		
		Without capture	With capture	Capture penalty	Without capture	With capture	Capture penalty
Fuel input (MW, LHV)	MW, LHV	2371.1	2371.1		2371.1	2371.1	
Gross power output	MW	1048.8	919.0		1048.8	950.0	
Ancillary power consumption	MW	36.3	110.6		36.3	80.2	
Net power output	MW	1012.5	808.4		1012.5	869.8	
Efficiency	% LHV	42.7%	34.1%	8.6%	42.7%	36.7%	6.0%
CO_2 emissions	g/kWh	758.4	97.6	0.9	758.4	437.7	0.4
CO_2 captured	g/kWh		852.3			445.2	
% CO_2 emissions captured			0.9			0.5	

		MEA 90% capture	MEA 50% capture
Scaled ancillary w/o capture	MW	36.3	36.3
Additional capture ancillary consumption	MW	74.3	43.9
CO_2 captured	t/hr	689.0	387.2
Specific power consumption	kWh/tCO2 captured	107.8	113.4

One of the advantages of ASPEN is the ability to optimize the simulation result by varying different parameters for the process. Temperatures, pressure, concentration of solvent are all important factors for the operations of the capture unit. This section shows when the capture rate is 50% how the electricity output changes from the power plant (see Table 5-9).

The power required for capture per tonne of CO_2 is higher in the 50% scenario than in the 90% scenario. This value is calculated from the amount of power generated divided by the total amount of carbon dioxide captured and the relation of the power output is not directly link to the amount of the carbon captured, but the heat that is needed to generated carbon dioxide from the power. Reasons that the 50% percent scenario is selected is that the amount of carbon dioxide captured per kWh of electricity produced is then similar to the amount without 90% capture at natural gas power plants, also emissions per kWh are similar to natural gas power plants without capture.. Also, stakeholders are interesting in partial capture instead of full capture as will be discussed in section 7.

5.4 Results analysis

The results for the whole simulation were obtained automatically from ASPEN and are shown in the Appendix 2 as mentioned previously. In this retrofit case, the power plant operating condition is unchanged and is not included in the optimisation analysis. The optimisation result for the MEA capture unit shows that

a. Extracted steam for desorber should come from the stream before the low pressure turbine rather than the low pressure heater.

b. The total efficiency drop is 8.6% in the simulation and the CO_2 avoided is 852.3g/kWh for 90% capture.

c. A 50% capture rate of CO_2 will change the efficiency drop to 6% at a CO_2 avoided rate at 445.2g/kWh. However, the specific power consumption will increase from 107.8 kWh/tCO_2 to 113.4kWh/tCO_2.

5.4.1 Limitation of the model

The limitation of the model includes:

1. The load factor for the base load plant could reduce to 50% -60% for a more realistic case in China and the efficiency could change accordingly.

2. As this is a retrofit case, none of the equipment that the power plant original had installed has been modified. In a real retrofit case, more equipment needs to be considered and the parameter for the basic power plant might change.

3. ASPEN is similar to an input-output model, some detailed reactions inside a reactor model might not be a fully accurate representation of a real power plant with respects to the behaviour of catalysts or packing for the reactor. This has not been explored in ASPEN.

4. A power plant involves much more equipment than is shown in the process flow diagram. Some of the equipment shown here might represent two or more elements of equipment in a real power plant. In this simulation, the equipment blocks are set up to have the same output as a group of separate units. But in reality, such equipment might be difficult to manufacture as a single entity.

5.5 Required data for ASPEN simulation for PC plant

Table 5-10 Data for feed streams into ASPEN

<table>
<tr><th colspan="3">Data</th><th>Unit</th><th>Notes</th></tr>
<tr><td rowspan="12">Coal</td><td colspan="2">Coal flow rate</td><td>Tonne/hr</td><td></td></tr>
<tr><td rowspan="6">Ultimate analysis</td><td>C</td><td>%</td><td></td></tr>
<tr><td>H</td><td>%</td><td></td></tr>
<tr><td>S</td><td>%</td><td></td></tr>
<tr><td>N</td><td>%</td><td></td></tr>
<tr><td>O</td><td>%</td><td></td></tr>
<tr><td>Others</td><td>%</td><td>If available</td></tr>
<tr><td rowspan="4">Proximate analysis</td><td>Fixed carbon</td><td>%</td><td></td></tr>
<tr><td>moisture</td><td>%</td><td></td></tr>
<tr><td>Volatile matter</td><td>%</td><td></td></tr>
<tr><td>Ash</td><td>%</td><td></td></tr>
<tr><td>Air</td><td colspan="2">Air flow rate</td><td>Tonne/hr</td><td></td></tr>
<tr><td rowspan="2">water</td><td colspan="2">Water flow rate for limestone</td><td>Tonne/hr</td><td></td></tr>
<tr><td colspan="2">Water flow rate for supply water</td><td>Tonne/hr</td><td></td></tr>
<tr><td rowspan="3">Steam flow rate</td><td colspan="2">Main</td><td>Tonne/hr</td><td>Steam flow rate for superheater</td></tr>
<tr><td colspan="2">Reheater</td><td>Tonne/hr</td><td></td></tr>
<tr><td colspan="2">Economizer</td><td>Tonne/hr</td><td></td></tr>
<tr><td>Ammonia</td><td colspan="2"></td><td></td><td>For NOx reduction (SCR method)</td></tr>
<tr><td>Limestone</td><td colspan="2">Consumption rate</td><td>Tonne/hr</td><td></td></tr>
</table>

The above section simulates the conventional units' operation condition at a power plant. The ASPEN package can provide greater confidence for other capture ready plant when planning for the retrofit work. A realistic flue gas analysis could be easily achieved by entering the key data for the power plant. For different power plants, the data for feed streams are listed in Table 5-10:

When building the pulverised coal plant model, only data listed in Table 5-10 and Table 5-11 (for pressure and temperature for key units) are needed for each simulation. This simplified process can greatly reduce the time and work required when analysing power plant retrofitting, as in most cases the data will be available in the feasibility study or the operation handbook. With the help of the simulation package, the flue gas analysis and simulation for the capture retrofit unit can be calculated much more easily by the thermal power plant engineer. As traditionally, the education and training for the thermal power engineers in China are limited to fundamental thermodynamic science or machine operating skills in most cases (based on interview experience with thermal engineers in China). Carbon capture and storage as a new subject, combines not only the knowledge from power generation, but also process technology and storage expertise.

Table 5-11 Parameter for main reactors (the input for Zhouxian is shown here)

Item	Symbol		Example for Zhouxian		Description
			In	Out	
Boiler	P	MPa	26.25	26.25	Inlet and outlet dater for steam at superheater
	T	^{o}C		605	
Reheater	P	MPa	5.09	4.89	Inlet and outlet dater for steam at reheater
	T	^{o}C	356.3	603	
Economizer	P	MPa	30.45	26.25	Economizer data for flue gas and water
	T	^{o}C	302.4	342	
1. P: Pressure (MPa); T: Temperature (Li, Zhou et al.)					

5.6 Conclusion

The ASPEN simulation model for post combustion capture plant can transform the idea of "how a power plant can be retrofitted" into a simple engineering modelling task, that requires only a limited amount of data from the plant operators, but can calculate and give out the equipment changes, efficiency changes, power output changes and the impact of different level of carbon capture applied at the power plant.

The simulation can also provide easy assessment for different levels of carbon capture. The total amount of carbon dioxide captured for per kWh of electricity can vary in the modelling in order to compare with other power generation technology. The partial capture idea is also welcome by many of the stakeholders, as will be discussed in chapter 7.

Another advantage of the model is that it not only provides solutions for the capture retrofit case, it also assists the engineers to understand better about the requirement for capture ready design. Although for capture ready design it is assumed that the technology could be improved by the time the retrofit is required, the fundamental features for each type of capture technology will not change greatly over this period for a typical plant. In this case, only the capture unit would need to be redesigned and modelled, while the main power plant could remain the same.

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Chapter 6 Carbon capture ready for pulverised coal plants in China

More PC plants will be built in the next couple of decades in China. In order to prevent carbon lock-in for those plants and reduce the possible cost for retrofitting those plants, carbon capture ready is essential for power plants in planning. In this chapter, suggestions on capture retrofit design and planning are given based on the power plant layout and operating parameters studied in Chapter 4 and Chapter 5. The common coal–fired power plant layout is summarised at the beginning of this chapter, some factors that could affects the capture ready decision is listed, a method for selecting capture ready plant is given and an example of regional planning is shown at the end of this chapter.

6.1 Generic power plant parameter

6.1.1 Common coal-fired power plant layout

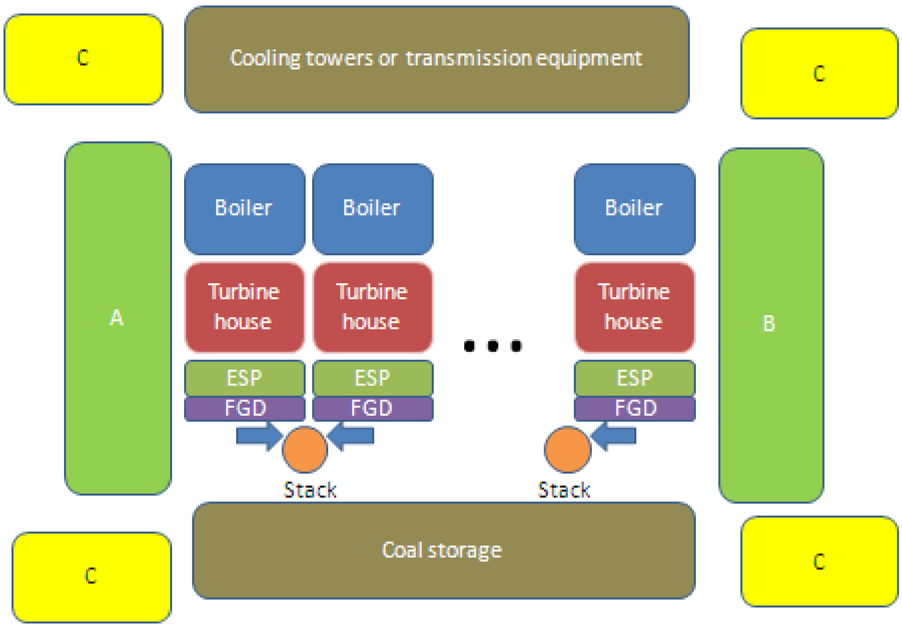

Figure 6-1 Power plant layout

As discussed in the previous session, most power plants in China, especially the generating units, share a similar layout to that shown in Figure 6-1. The electricity generation units are built very tightly in a single row with pairs of units sharing a stack. Coal storage, cooling towers and the transmission equipment are built at either the top or bottom of the generation units as shown in the figure. It is rather rare to have the transmission equipment built at location A or B. Normally, location A and B are left empty or as a small green band in the power plant. Occasionally, the coal storage units are built are location A or B when the "coal storage" is built next to a river or at water front. The administration office and administration office normally occupies location C.

6.1.2 Power plant technical data summary

Shanghai Boiler, Dongfang Boiler, and Harbon Boiler dominate the advanced boiler market in China, especially for the 1000MW ultra supercritical and 600MW supercritical types. Table 6-1 summarises the most popular boilers from some of the big manufacturers in China. Although the boilers are designed differently, the technical parameters for a certain size of boiler are similar. For example, the main steam flow for 1000MW ultra supercritical boilers is between 2,950 and 3,100 tonne/h and the main pressure between 26.15 and 27.56MPa. The small difference in parameters means that the ASPEN model (Chapter 5) simulation for the capture ready or retrofit case can be easily modified. Hence, when planning the capture ready case, the variations for the simulation model can be grouped into a few scenarios.

Table 6-1 Boiler orders from boiler company (Linkschina 2009)

MW	Type[1]	Company	Main steam flow (t/h)	Main pressure (Mpa)
1000	Ultra supercritical	DG	2060 or 3033	26.25 (one unit at 27.56)
600	Supercritical	DG	1900 or 2070	25.4
1000	Ultra supercritical	HG	2950, 3033 or 3100	26.15, 26.25 or 27.56
660	Ultra supercritical	HG	2000 to 2098	26.15
600	Ultra supercritical	HG	1795	26.15
600	Supercritical	HG	1890-2100	25.4
600	Supercritical	BG	1950	25.4
1: DG: Dongfang Boiler; HG: Harbin Boiler; BG: Beijing Boiler 2.Infomation for Shanghai Boiler is not available at the time of writing the thesis				

6.2 Carbon capture ready plant site selection methodology

Site selection is one of the most crucial factors when deciding to build a power plant to have capture ready status. The methodology for storage site selection is well developed (Bachu 2000; Kuuskraa and Pekot 2003; CO2RC 2008; Grataloup, Bonijoly et al. 2009) and the IPCC (2005) report considered site selection as the fundamental step for the success of a CO_2

storage operation. The importance of site selection has so far been emphasised mainly in connection with carbon storage operation rather than carbon capture plant site selection. However, site selection methods for other types of power generation technology, such as nuclear power plants, solar power plants, incineration plants, wind farms, biomass plants, have been published in the literature (Kutbi 1987; Shi, Elmore et al. 2008; Bistline and Rai 2010).

Unlike solar power plants, wind farms and hydrogen plants, which are localized and generally resource dependent, the criteria for potential carbon capture ready plants could be distance to the storage site, the capacity of the storage site, power plant parameters. Hence, the site selection process is time and expertise consuming. Screening of potential capture ready plants requires consideration of a combination of factors, both qualitative and quantitative. The proposer not only needs experience in power plant planning but also a fair amount of geological information about the site. One of the aims of this thesis is to develop the methodology for a user friendly tool which makes it easier for policy makers and power plant investors to perform the complex evaluation.

Currently, the carbon capture ready plant site selection process has not been applied to any power plants, because there is no large scale existing infrastructure for carbon dioxide transportation. However, for the storage sites such a selection process has been developed. One of the two-step methods that could be adopted in the capture site selection (Grataloup, Bonijoly et al. 2009) involves:

- Meeting all "To be or not to be criteria" that define potential sites locations before entering the next level of assessment
- Assessing the "bonus criteria" that can create a ranking table for decision making based on the contending sites for a particular project

6.2.1 Legislation factor

Most countries have legislation on power plant siting, which covers the distance to residential areas, site location topography, and emission limits. This means carbon capture plants must fulfil the requirement of all the factors mentioned in the domestic legislation documents and pass several regional regulations concerning environmental impact. For some countries, such as the EU and the US, the rules are stricter than others. Some typical factors (the guidelines in this section will based on the case for Chinese power plant (CECC 2000) include, but are not limited to:

a) Distance to residential areas

All new built power plants are advised to be located away from residential built-up areas and from the outskirts of any major city.

b) Distance to coal mine

As one example, the guidelines suggest that low quality coal be consumed at the coal mine whilst high quality coal could be shipped for longer distances.

c) Unit number, capacity and technology

It is suggested that power plants built at the same site should have no more than six units. If the capacity of different unit varies, it should have at most two different installed capacities amongst all the units. For units with the same installed capacity, when the main equipment (such as boiler and turbine) are the same, the supplementary equipment should also be the same.

d) Distance between equipment

As one example, in a power plant in China the cooling tower needs to be at least 20 meters away from all other major units. Other space limitations applied to the major power plant units varies between 5 meters to 60 meters in China.

These are typical factors that most power plant designers have taken into consideration before laying the foundation for the plant, which are normally found in regulation handbooks or design guidelines and are rarely violated by plant designers. Given the nature of a CO_2 capture plant (which is more or less a chemical processing unit plus compression unit on the site of a power generation site), the legislation applicable to chemical plants should also be followed.

Siting for the CO_2 capture unit and the size of the unit to accomplish full scale carbon capture should therefore be carefully considered rather than relying on the rough estimation of open space available.

The legislation for carbon capture ready does not need to be in place before power companies start building capture ready power plant, providing the companies can get the extra land. The case is similar to the FGD ready and DeNOx ready planning in China. Power plant developers are voluntarily building their plants in a way that can be retrofitted for sulphur and NOx reduction. Subsequent experience has already endorsed the decisions made in the early 2000s to build many power plants in an FGD-ready state and they have now been retrofitted to a SOx capture plant after regulation on SOx emission level was introduced. Currently, there is no strict legislation on NOx emission in China. Most of the advanced power plants have air-staged low NOx burners installed in the boiler to control the NOx level at below 450mg/m^3. Plants with low NOx burners can reach a NOx emission level of 200mg/m^3 (from the Zhouxian's case in chapter 5), which is half of the national standard. However, in many cases, there is space reserved for the DeNOx unit at these advanced plants, with the expectation of much tougher legislation on NOx emission of below 100mg/m^3 being passed within the plant operational lifetime. It is possible that carbon capture could happen without any strict legislation – Chapter 7 will discuss this in greater depth.

6.2.2 Engineering factors

The success of a capture ready plant relies on technical and engineering assessment before the plant is built. The essential part of making a power plant capture ready is the ability to retrofit the plant at a much lower capital and operational cost than a plant not designed to be capture ready. In many current cases the power plant location and operational conditions are decided first before the planning for carbon capture readiness and the later modification to capture ready status acts as a symbol to show that the investors are keen to tackle climate change. Therefore, the capture ready plant preparations cannot be considered as an integrated part of the power plant, but rather a possible bonus for a completed system that happens to have suitable circumstances. In a real capture ready case, the design power plant operational conditions, especially for the water-steam cycle and gas clean up system should be included in the initial power plant planning to avoid extra efficiency penalty after retrofit such as adding additional pipeline connectors from the intermediate pressure turbine for supplying steam to the capture plant.

For those plants that are planned from the beginning with capture ready design as an integrated process, computational simulation is a good way of avoiding extra cost and getting the best performance after retrofit. In contrast to legislation, the engineering factors do not “create” capture ready power plant, but optimise the outcome of a capture ready power plant. Only after the engineering factors are considered when designing the capture ready plant can the plant be operated with capture at a much lower cost.

6.2.3 External factors

The external factors are defined as the quantitative features that affect the CO_2 transportation and storage cost after retrofit. It should be used as the primary tool to evaluate the location of a capture ready power plant when the decision is market based rather than a decision taken on the location of a demonstration or other high profile project, which is mainly policy driven in China.

1. Distance to storage site

   The distance from the emission point to potential storage is a key factor for deciding whether a plant should be built carbon capture ready. The assumption is that when carbon capture from power plant is implemented in China, the carbon dioxide will be transported through a pipeline. As the IPCC (2005) report suggested, rail and road tankers are unlikely to be considered attractive options for large scale projects, since they cost more than twice as much as a pipeline. Long distance pipeline transport also requires additional booster stations to maintain the pressure. When the pressure is over 9.6MPa, pure carbon dioxide will remain at a dense phase state at all temperatures, which can reduce the diameter of the pipeline compared with gas phase transport (IPCC 2005).

2. Diameter of the pipeline

   The diameter and thickness of the pipeline will also affect the total pipeline cost. When a pipeline passes through a densely populated area the pipeline need to be manufactured with thicker walls than where it passes through rural areas. An example is the Cortez pipeline, which is the longest and biggest in terms of capacity, it is 762 mm in diameter and passes through villages and countryside (Morgan 2010). The pipeline currently transports 19.3 Mt CO_2/yr to a destination 808km away.

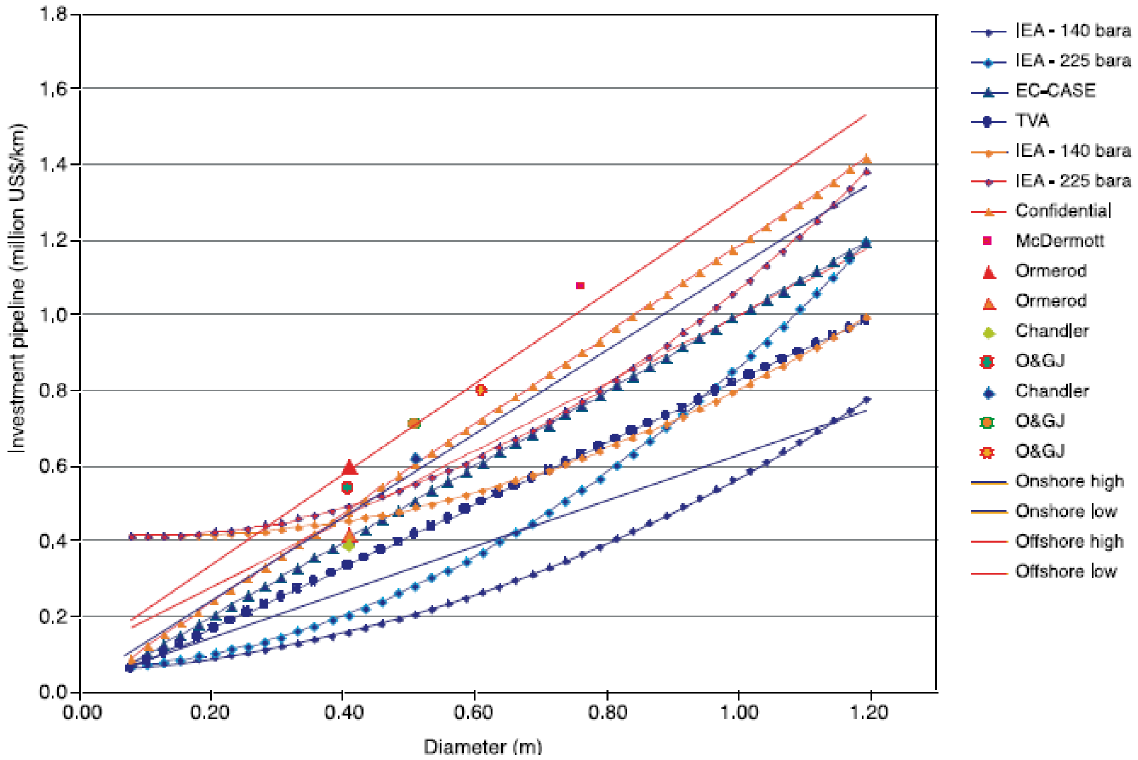

Figure 6-2 Total investment costs for pipelines from various information sources for offshore and onshore pipelines. Costs exclude possible booster stations (IPCC 2005)

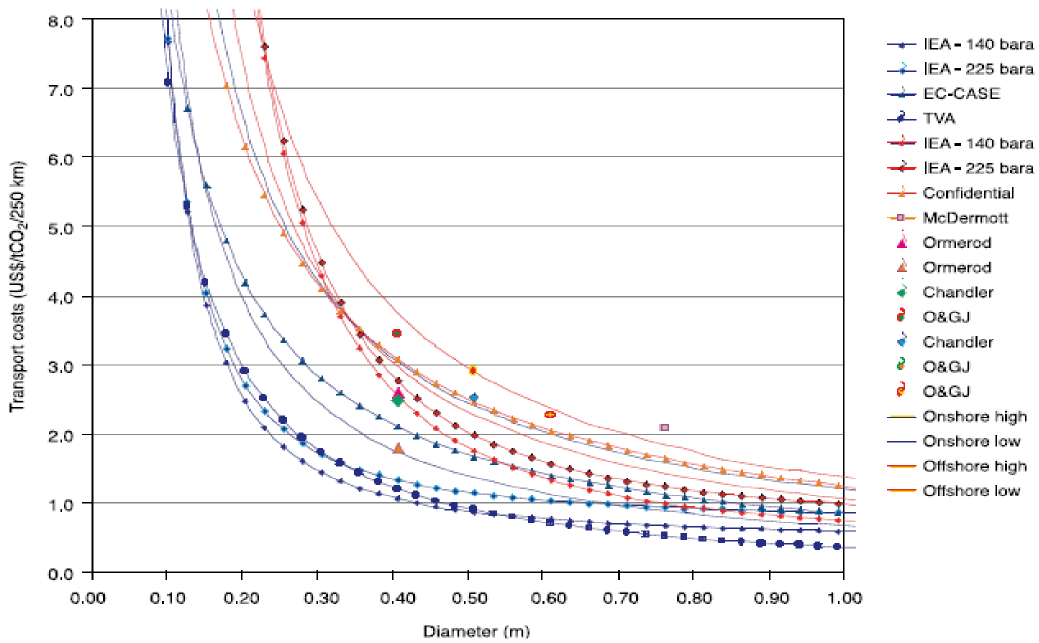

Figure 6-3 Transport costs derived from various information sources for offshore and onshore pipelines. Costs exclude possible booster stations, applying a capital charge rate of 15% and a load factor of 100% (IPCC 2005)

Figure 6-2 and Figure 6-3 show the cost estimates for various pipeline diameters. The cost benefit of having power plants built relatively close together and sharing a main pipeline can be observed from the figure and a possible solution is suggested in section 6.4.

3. Nearby generation unit

   Scaling up pipeline capacity could create economic benefits for power plants that could share a large pipeline to transport the carbon dioxide. Planning a new power plant next to existing ones would exploit this advantage. Against this principle, for example, the regulation limiting the installation of only two different unit sizes at one site has forced several large sized plants to be split into two operating companies, such as the Zhouxian 1000MW power plants (as described in section 5.1.3). This also raises problems stemming from historical issues when plant was built by different investors, such as the power plant in Shajiao, Guangdong. In the extreme case, a power plant with a big enough installed capacity might be able to construct its own pipeline to a storage site. To summarise, the capture ready plant should consider if it is:

   - built next to another power plant
   - big enough to have its own pipeline transport system

4. Geography factors and public perception

   The cost of a pipeline can increase by 50% to 100% or more when the route is congested and heavily populated (IPCC 2005). Typical factors that could increase the cost are: mountain areas, nature reserve areas, rivers, railways and roads, and the requirement to monitor in populated or highly valued areas. Offshore pipelines are often 40 -70% more expensive than onshore pipelines, but gain permission more easily. The Cortez pipeline mentioned previously passes through two populated areas, the pipeline route is clearly marked through the residential areas and regular information briefing sessions were given to local residents for risk and safety purposes. But for areas with a high percentage/large number of temporary residents, the need for frequent briefing sessions could add extra operational cost. In the coastal areas of China for example, where the temporary population is normally much bigger than the permanent population, it is difficult to guarantee that everyone gets the chance to know the hazards of carbon dioxide if a leakage happens.

6.3 Carbon capture power plant ready site selection

6.3.1 Site selection factors

The site selection step is based on those principles previously listed and the check list in Table 6-2. The criteria can be classified into two categories: "To be or not to be criteria" and "bonus criteria". "To be or not to be criteria" is the first stage a site must satisfy and only those plants that can fulfil all the requirements should enter the next selection stage. The "bonus criteria" can create a ranking for those candidate plants that have passed the first selection procedure. Therefore, a league table can indicate the most desirable locations for the capture ready plant, based on Table 6-2. Six focuses are defined for the primary factors when making decision on capture ready plants. These are the operating condition of the power plant, transport of carbon dioxide, storage, social concerns, risk and regulation. For each of the focuses, several "Type" segments are made to simplify this big subject. And each "Type" segment will have some "Criteria" that break down the semi-segments into details.

6.3.2 Assessing the site selection factors

When evaluating the best site in accordance with the factors discussed in Table 6-2, a spider chart can be used to calculate the rating of a specific plant as shown in Figure 6-4. This is a novel approach for CCR plants assessment, as the spider chart is normally used in marketing test for new product. Although CCR plant is not a new product that targets a certain market segment, it shares some similarity to actual products. For example, the investor might not be as familiar with the CCR concept, in the same way as the consumers do not know a new product well. The process of working through the spider charts to determine which is the best plant location from a group of potential candidate capture ready plant sites is similar to defining what is the best market segment for a new product.

Table 6-2 Site selection table

Focus	Type	Criteria	Object/area	Impact factor[21]
Power plant flexibility	Capture flexibility	Easy switch for capture and non-capture	Power plant	High
		Capture efficiency	Power plant	Low
	Energy penalty	Reduce energy penalty for capture plant	Power plant	High
	Water consumption	Reduce water consumption for solvent	Power plant	Low
Transpor-tation Optimisa-tion	Capacity	Changes in transport capacity	Pipeline operator	Medium
	Flexibility	Changes in operation condition	Pipeline operator	Medium
		New receiving terminal	Pipeline operator	High
	Capacity	Storage type	Targeted site	Low
Storage assessment	Accessibility	Storage lifetime	Targeted site	High
		Location	Targeted site	High
	Monitoring	Injection	Targeted site	Medium
		CO_2 movement	Storage area	Medium
	Worker	Leakage	Storage area	High
		New job	Related industry	Low
Social and economic benefit	Manufacturer	New career development	Related industry	Low
		New order	Related industry	Medium
	Regional Government	Industry upgrading	Tax income	High
	Local resident	Better environment	Environmental protection agent (EPA)	High
		Knowledge on climate change	Education sector	High
	Power supply unstable	Sudden changes in electricity demand	Power plant	Medium
Risk analysis	Leakage pathway	Pipeline damage	Pipeline	High
	Storage failure	Sudden geological changes	Targeted site	High
Regulation	Land use	Capture ready space reserves	Local planning office (LPC)	High
	Emission standard	Pipeline planning	LPC and oil company	Medium
		Storage space	Oil company	High
		Upgrading gas cleaning system	EPA	Low
	Transportation standard	Changes in capture efficiency	Power plant	Medium
		Upgrading CO_2 receiving requirement	Power plant	Low
	Waste disposal regulation	More rules on CO_2 handling	Storage site	High

[21] The impact factor is given based on the author's experience through her research in CCS. Different people could have different interpretation on the impact factor.

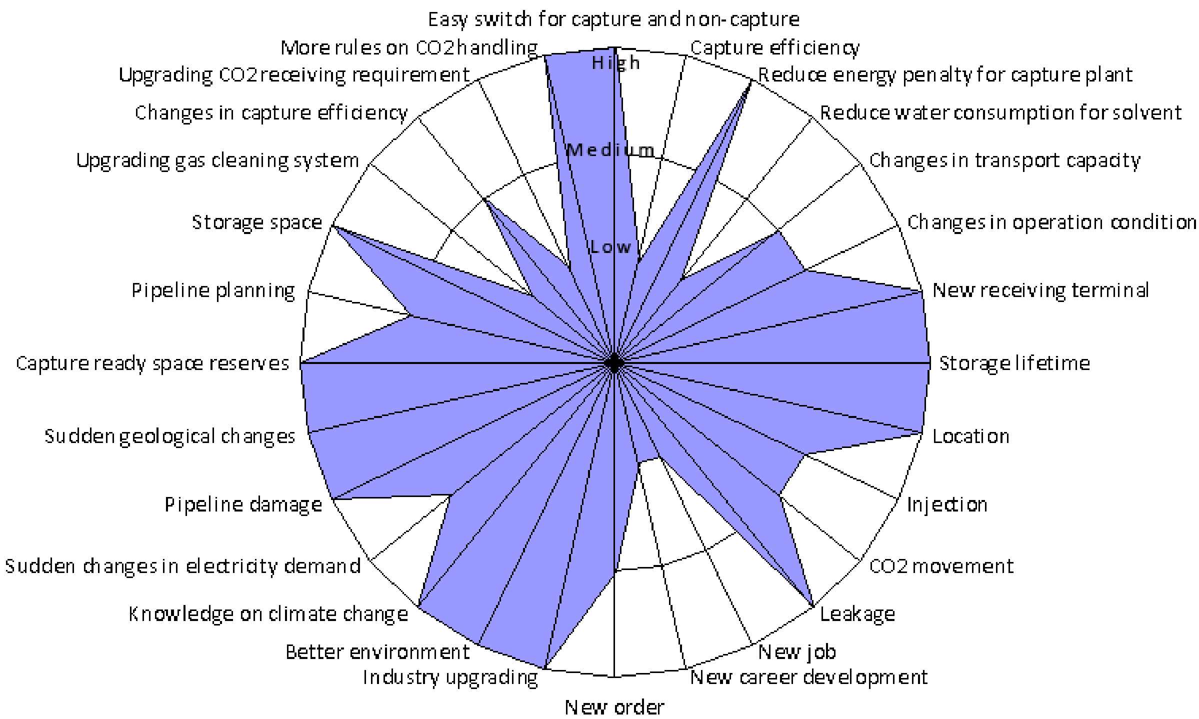

Figure 6-4 Site selection spider chart

The spider chart template is equally divided by the factors mentioned in 6.3.1 and connected based on the impact factor listed in the same table. Each factor is represented on a star-shaped figure with one ray for each factor. For a given criteria, the length of each ray is made proportional to the size of that factor. The assessment work involves ranking each factor with a number ranging from 0 to 100, with 100 meaning the best plant performance on the particular point. The scoring for each factor will be shown on the spider chart according to the impact factor. If the impact factor is high, a score of 100 means the scoring dot will fall on the outer circle (the high circle) of the chart. If the impact factor is low, a score of 100 means the scoring dot will fall on the inner circle (the low circle). After all the dots are plotted and joined together, the total area inside the connected area divided by the size of the spider template area is the ranking for an individual plant. If several plants are being assessed at the same time, the highest ranking plant is likely to be the best site for carbon capture and storage.

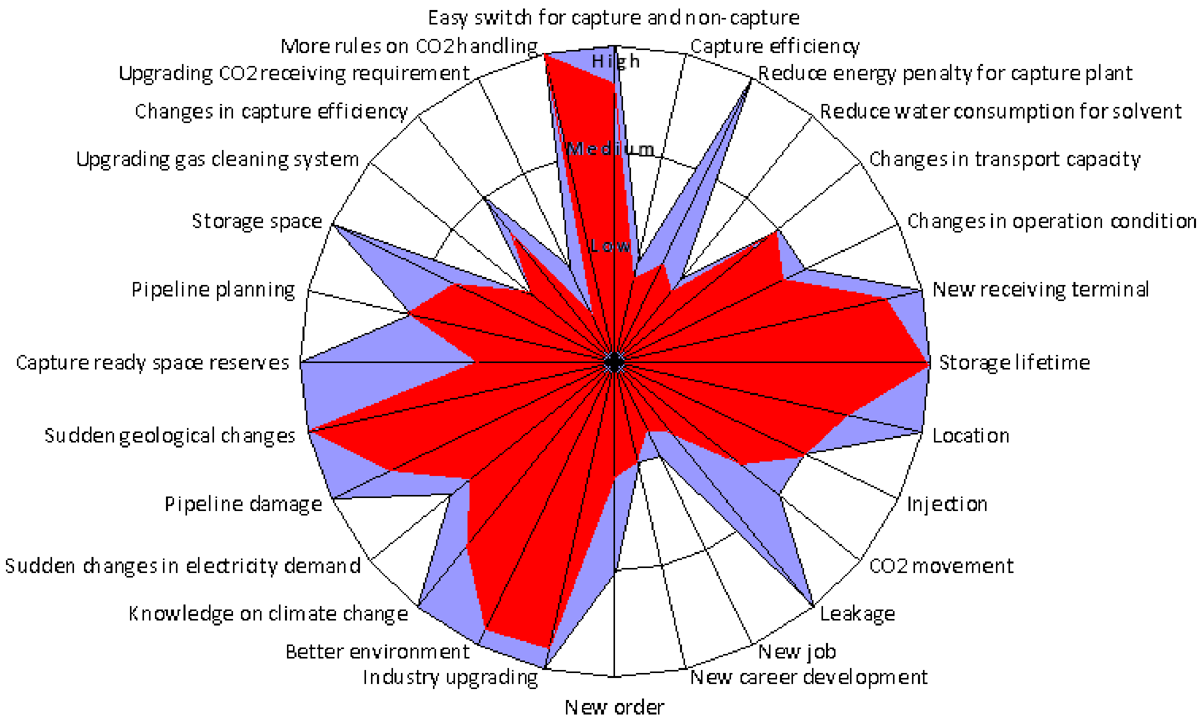

Figure 6-5 Example of site selection ranking with spider chart

Figure 6-5 shows an example of how spider charts work when deciding the site location for a capture plant. Each point on the ray represents the scoring for the criteria of a chosen power plant, and the total area in red or blue divided by the total area of the circle is the ranking for the power plant.

The spider chart can transform the site selection method from a qualitative into a quantitative assessment. It is a scoring system based on a series of subjective assessments, but capable of reducing individual bias, especially if more people are involved in the assessment of a particular plant and pre-defined sets of criteria for each scoring level in a particular category are drawn up and applied.

6.3.2.1 Limitation of the spider chart

The spider chart has an advantage when several potential sites are proposed as a capture ready site. However, when there is only one site being offered, the scoring for that particular site is not an absolute measure; it has value only for assessing relative superiority amongst a number of sites. Moreover, the impact factors shown here merely demonstrate the author's preferences based on years of research in this field. Different engineers might hold different opinion on the impact factors. Hence, the impact factor can be subjective and additional measures should be taken to establish standardised criteria before it is used as an assessment tool.

6.3.3 Site selection decision making process

A number of studies on source and sink matching for carbon capture and storage have investigated the possibility of transportation routes for large stationary emissions (Herzog, Li et al. 2007; Chen, Teng et al. 2008; Lone 2009), which are relevant when deciding the infrastructure to support the capture ready plant. Potential pipeline routes can be modelled by GIS software once a specified storage site has been chosen. However, the difference in simulating capture ready plant compared to existing emission sources is that capture ready plants do not exist at the time of planning. Hence, the most cost saving way of planning is to build the power plant based on the existing pipeline simulation results from GIS software, instead of building a new connecting pipeline to the simulated pipeline route. In addition, this modelling largely depends on knowledge of "known" geological factors. Consequently the research for capture ready power plants should not focus on the best economic pipeline layout for the existing emission points, but be customised to fit power plants into some of the existing pipeline corridor networks, such as natural gas pipeline, water pipeline., in an economic way.

If a plant could be built along an existing pipeline (or GIS simulated pipeline route) with enough capacity to handle the additional gas volume, this would save a lot of investment for the new plants, and represent an excellent opportunity for new investment in a capture ready plant. However, the decision making process currently does not start from the viewpoint of storage accessibility, but from the power generation side. See Figure 6-6 for the decision making process for capture ready plant. The current site selection process starts from the electricity demand side. When electricity demand is forecasted to exceed supply, the board of the electricity supplier will make an investment decision. The site of a new power plant to be built will then be selected before considering having a carbon capture unit.

The ideal capture ready site selection process should start with the plan to build a plant which is in capture ready status. The next choice should be the most economic place to site the plant, before evaluating the electricity demand for the selected region, as electricity grid development is rapid in China. The final decision will then have a better impact on the capture ready design rather than one made only on the electricity demand.

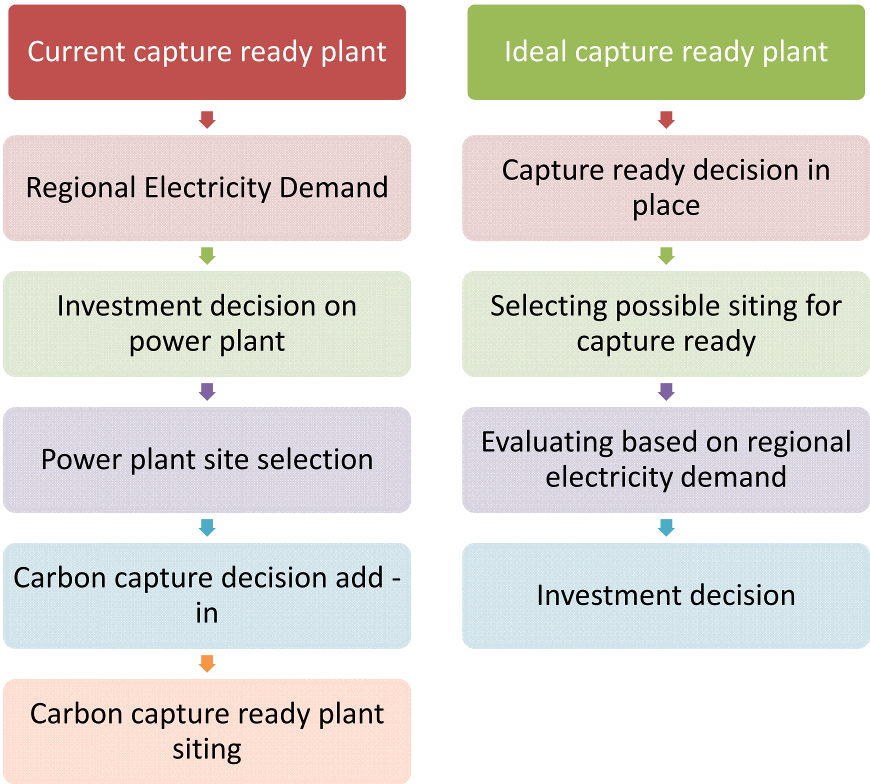

Figure 6-6 Decision making process for capture ready plant

6.4 Regional carbon capture ready planning

The criteria for site selection for capture ready plants include site specifications, such as engineering, legislation, geological and external factors, accessibility of the site by pipeline, proximity to coal resources, availability of industrial infrastructure and technical support, plus many other economic, social and environmental factors. Such criteria, however, vary from country to country, from region to region, depending on the prevailing regulations and plant specification. The importance of regional variations in the specification and planning for capture ready plant has been identified after the issue was raised during the Global Carbon Capture and Storage Institute (GCCSI) roundtable workshop on CCS Ready in China in 2009.

For the previous section on capture ready, the focus is on investors' decisions on new plant locations. In this part, the planning issue is made a major effort to give local authorities and government an idea of how they could help to accelerate the capture ready development.

Industry could also use this approach to try to benefit from the rules that might be written in the future.

The APEC[22] (2005) study on storage capacity assessed the potential of CO_2 storage in the Asia Pacific region. The results from their study show the northern part has a high prospectivity for storing CO_2 in the pink coloured sedimentary basins, which have many on-shore oil and gas fields. The western part has a low prospectivity for storing CO_2; however there is the possibility of enhancing gas recovery (EGR) in those regions. The southern and east part of China has a medium/unknown prospectivity to store CO_2 offshore in gas fields in the South China Sea. This is similar to the UK, where it is proposed to store CO_2 in the North Sea. When considering storage potential offshore storage is simpler than onshore storage. As many people hold the opinion of "not at my backyard" for CO_2 storage.

In order to find an early demonstration region in China, four factors need to be taken into account. The first and most important one is the access to storage site, which means there are storage sites within reasonable distance (normally less than 300km, but some sites have a longer distance) and it is possible to gain access to these sites. The second one is the availability and the amount of carbon dioxide emission points, which mainly means power plant or other large stationary emission sources should be grouped reasonably closely together and be possible to retrofit. The third is the financial support; CCS will first happen at a place where end electricity user can afford the extra cost of carbon capture and investors are ready to pay for the initial investment. The last one is peoples' interest in climate change and acceptance of CCS.

The coastal, coal-rich areas in China are more economically developed than other part of China. Guangdong, Zhejiang, Jiangsu and Shandong, Inner Mongolia provinces are amongst the richest ares in China. The author has chosen Guangdong as the case study in this thesis, because it is close to the South China Sea for potential storage, the electricity generated in this area has always been one of the top in China (see Table 3-1), it has a high GDP and the government is keen to work on environmental related issues.

[22] This is by far the most detailed study on storage prospect in China. Many storage data sets are not public data and is normally not possible to gain accessed to. The accuracy of storage has a high impact on the regional planning, as it affects the potential scale for the capture ready infrastructure. The Guangdong region which is chosen for this study has more detailed storage information available, provided by our partners in China.

6.4.1 Carbon capture ready in Guangdong

Guangdong province, China is used as an example for the capture ready study. Guangdong is China's largest provincial economy, has a higher GDP than Saudi Arabia, and is the largest export manufacturing producer in China. It has also been proposed to be China's first CCS-ready province, starting with a study funded by the UK Foreign and Commonwealth Office (UK FCO), the British Embassy in Beijing, China and the British Consulate Guangzhou, China (Li, Zhou et al. 2009). The aim is to provide initial work in a key province where CCS could be an integral part of China's low-carbon future. The aim of this project is to let government officers, local power plant owners become more aware of CCS technology and consider CCR in their decisions on new build power plants. If successful it would be a key step towards achieving a critical mass of commercial and political support for accelerated CCS deployment China- wide and internationally.

6.4.1.1 Background of Guangdong (Li, Zhou et al. 2009)

Guangdong (highlighted in purple in Figure 6-7) is an ideal location to develop CCS related issues. The province is proud of its legacy of being at the forefront of economic development. Party Secretary Wang Yang has referred to the need to develop a low carbon economy in Guangdong, which provides a high-level momentum for policy makers drafting the provincial Climate Change Action Plan and the 5 year Energy Conservation Plan. Guangdong is also China's province with the lowest energy consumption per unit of GDP. This presents challenges to the provincial government, who need to continue to find new ways to hit enhanced targets to reduce their intensity levels. It is generally accepted that Guangdong will be using fossil fuels as its main energy source for the foreseeable future. Guangdong is thus well placed to see the value in piloting CCR deployment. The provincial government currently views CCS as an unproven technology but there is a growing academic and business community active in the province which is driving for the development of CCS and CCR options.

The capture ready study will start by investigating the existing power plants with high volume carbon dioxide emissions. It will then address the regional planning for carbon capture ready plant. In this study, only plants with over 300MW units, supplying electricity to the national grid, will be investigated. This is because only the most recently built, large size, advanced plant are likely to have FGD[23] units fitted at the time of operation or might install FGD unit in the future, the older and less efficient unit faces a big possibility of shutting down in the future as explained in Chapter 3.

Figure 6-7 Location of Guangdong Province in China

6.4.1.2 Power plant emissions

By the end of 2009, Guangdong had 30 coal-fired power plants with units of over 300MW installed capacity connected to the national grid. The total installed capacity for those plants is 22.04GW, which is about half of the total installed capacity for all fossil fuel plants in the province. Another 9 units located at four plants have obtained planning permission and will start operation in the next 2-3 years. Figure 6-8 shows the location of these plants in Guangdong. As some plants are built next to others but run by different operators, the dots shown in the figure is less than the real number. The average coal consumption in terms of standard coal is 323g/kWh, 9g lower than the national average (CEC 2008), which has resulted from the wide implementation of newer, better performance generating units. Two plants do not have FGD installed at the moment. Two power plants started operation before the year 2000 and the majority started operation after 2003. The average unit operational hours per year in the province has dropped from 5,161 hours in 2006 to 4988

[23] FGD is used as an indicator because power plants without FGD fitted are not likely to operate for a long time due to environmental concerns.

hours in 2007 (CEC 2008), which is around 10% lower than the national average. Part of the reason is because of a lot of the small size oil power plants built in the 1990s are now used only during peak time. The power plants which are included in the study have average operational hours of 6,414 (73% load factor in average) hours per year (where information is available), with one plant operating at an extremely high 8059 (91% load factors in average) hours in 2008.

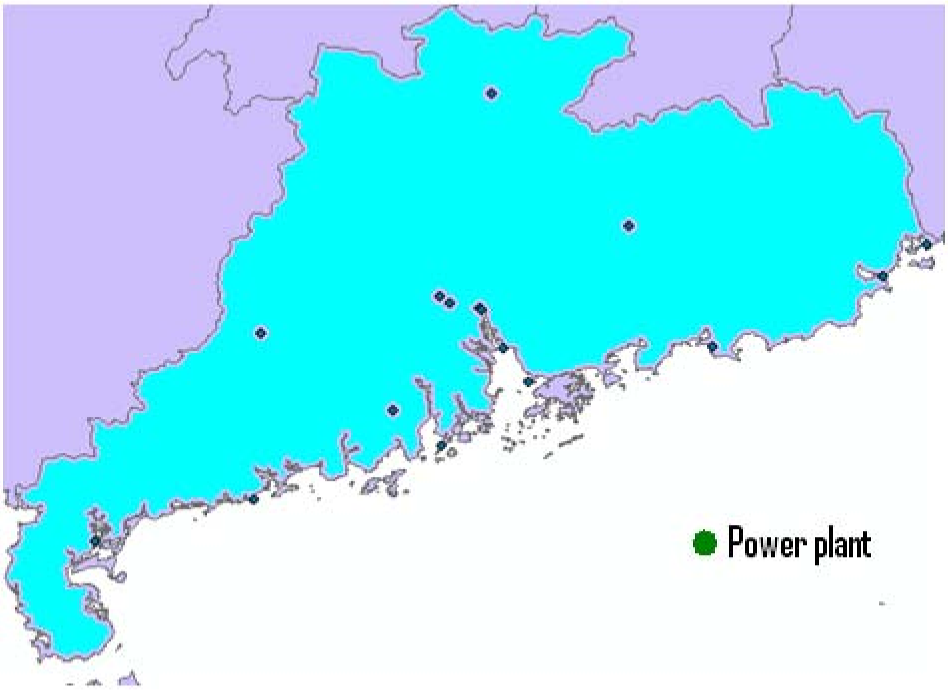

Figure 6-8 Power plants connected to the national grid in Guangdong

Figure 6-9 shows the power plant generation capacity by size within Guangdong. It can be seen that the Pearl River delta region has the highest amount of carbon dioxide emissions within Guangdong. Shantou and Zhanjiang and Shaoguan are also identified as having comparatively high emissions. The Pearl River delta has the highest density of power plants within Guangdong.

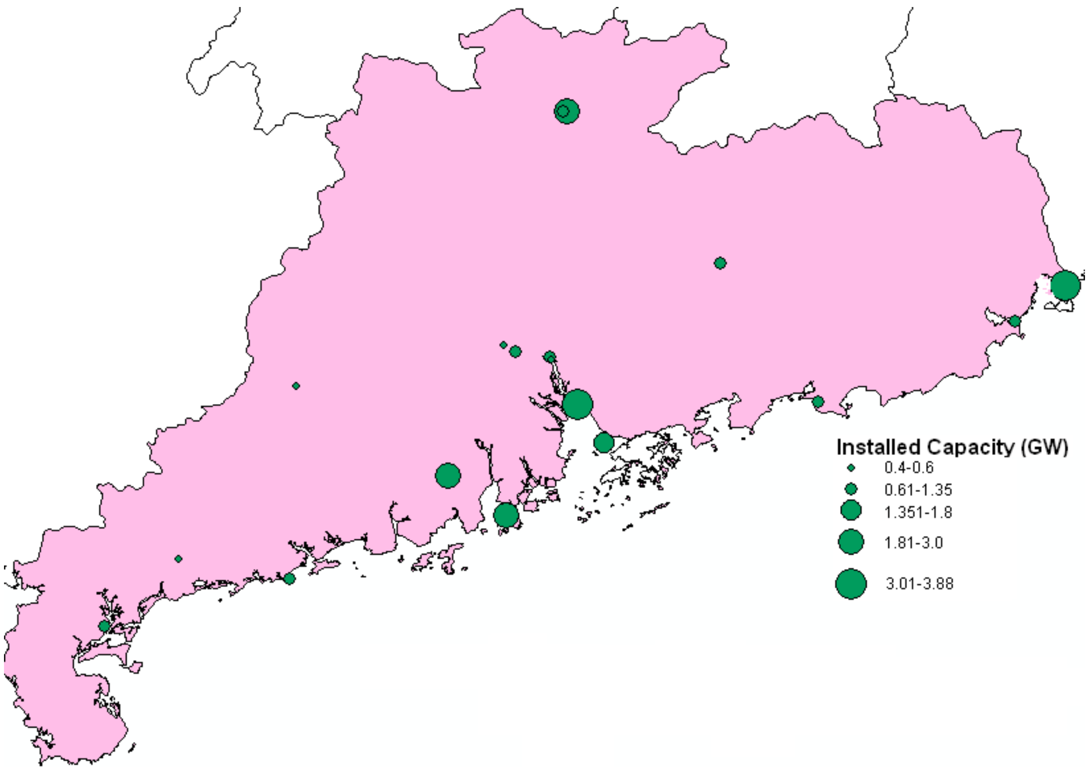

Figure 6-9 Power plants location with different installed capacity in Guangdong

6.4.1.3 Storage potential in Guangdong

According to Li (2009), the estimated carbon dioxide storage potential for Guangdong in saline aquifers, oil fields and gas fields is 93,760Mt, 60Mt and 12Mt respectively (see Table 6-3). This makes the total storage capacity of 93,832 Mt around the area, which is enough for 781 power plants with 1GW installed capacity to store all of the carbon dioxide emission during their 30 years operational life. This storage capacity is big enough to store all of the current emissions of China's coal-fired power plant. However, most of the storage opportunities are offshore in saline aquifers, making the operation and construction cost of pipeline and injection facility more expensive than the onshore option (See Figure 6-10 for site location). The onshore storage opportunity is 1,261Mt at the Sanshui basin, which is enough for storing all the carbon dioxide emitted from the units investigated in this thesis for 10 years.

Table 6-3 CO_2 storage potential in saline aquifer in Guangdong (Li 2009)

Basin name	Saline aquifer		Depleted oil field		Gas field	Total SC
	Size (km^2)	CO_2 SC	Increased oil production (MBO）	CO_2 SC	CO_2 SC	
Pearl River	83,028	68,700	89	41	12	68,753
Sanshui	3,000	1,260	2	1	N/A	1,261
Beibuwan	18,926	23,800	34	18	N/A	23,818
Total	104,954	93,760	125	60	12	93,832
SC: Storage capacity in Mt; MBO: Million Barrel						

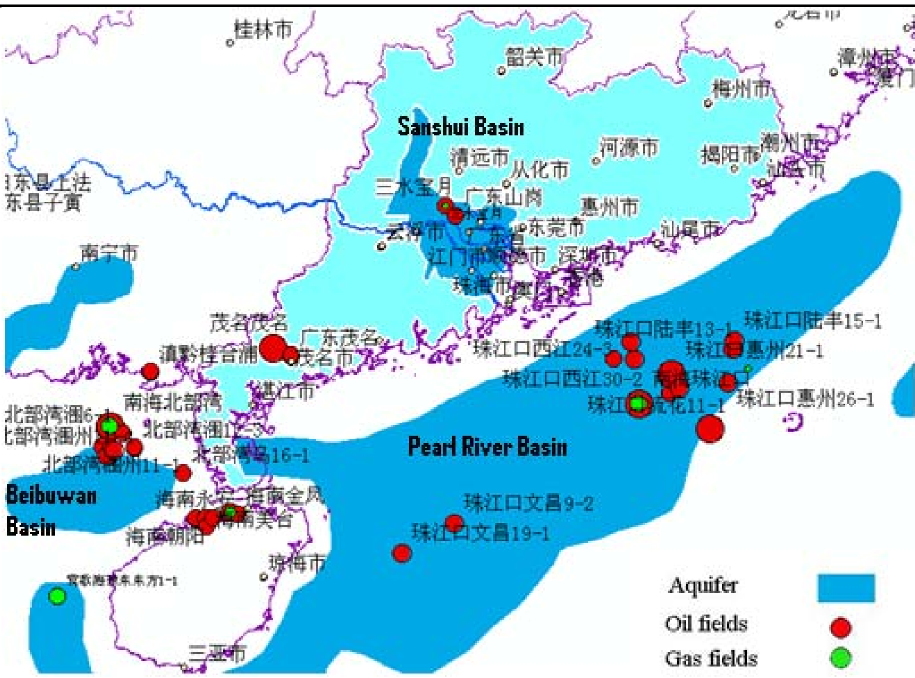

Figure 6-10 Potential storage sites in Guangdong (Li 2009)

1. Early stage Demonstration

The storage potential in the Sanshui basin provides an excellent opportunity before large scale pipelines for offshore storage are constructed. The Sanshui basin can also act as an early stage testing site in the region, given the fact that around 10 power plants are built within 200km of the potential storage site. The Sanshui basin was developed in the 1970s, but was generally abandoned in the early 80s after production fell and the discovery of the Beibuwan basin in Guangdong. Currently, only one oil field is still in operation producing 1-2 barrels of oil per day, with one gatekeeper at the site. During the exploration, a number of carbon dioxide wells were discovered. Because of the development and reform policy, the Sanshui area has transformed from a rural area into outskirts of the city of Fushan. Though most of the old oil production wells are still in rural areas, some of the high concentrated carbon dioxide wells are already surrounded by residential areas.

Table 6-4 CO_2 wells in high concentration in Sanshui Basin from my visit

No.	Production rate (m^3/d)	CO_2 concentration （%）	Notes
A	47400	83.99	Rural area
B	59128	99.54	Estimated to have 0.3 billion m^3, currently 0.1 billion m^3 is still in reserved, very close to residential area
C	412	99.48	Located at the entrance of a village, very close to motorway
D	N/A	97.41	This well was drilled in order to provide drinking water
E	N/A	89.64	Rural area, but rather close to a prison

Table 6-4 shows some of the typical carbon dioxide wells I visited in 2009. Well B, which is one of the biggest carbon dioxide wells in terms of storage capacity, had two major gases blow-outs between 1977 and 1981. It is now 50 meters away from a residential block (shown in Figure 6-11). Well D, which was discovered 40 years ago while local villagers were trying to drill for drinking water has disappeared in the fully developed village. Although this opportunity has disappeared, it shows the availability of carbon dioxide at a shallow level in the region. The location of well A, C and D are still in rural areas and have a high potential to re-inject carbon dioxide if that is geologically feasible. The area close to well A is shown in Figure 6-12. Many equipment items similar to that shown in Figure 6-12 are still at their original place. Hence, if carbon dioxide is to be stored in one of those fields, roughly 1 million CNY could be saved by using the existing well to avoiding drilling cost.

Figure 6-11 Well B at Sanshui Basin

Figure 6-12 Abandoned oil extraction well close to well A

Another potential onshore EOR (Enhanced Oil Recovery) site is in the south of Guangdong at Zhanjian, where the Beibuwan Basin is located. Oil production still contributes a fair amount of money towards the city's total tax income, however, detailed geological information is not available at the time this thesis is being written.

Some small coal mines are located in the north, which have been closed in 2005 because of safety. The potential storage capacity in coal beds is estimated to be 3Mt in total (Li 2009).

The early stage demonstration and CCS capacity building in Guangdong can rely on the onshore opportunity, because sources and sinks can be matched. However, it is a race against time with city development. If the city expands too quickly, the existing opportunity for wells similar to Sanshui's A, C and E will become as desperate as the situation with well B. Planning decisions might be non-reversible if those lands are earmarked to become industrial or residential areas. Therefore, regional planning of capture ready is important and crucial especially within the next 5-10 year.

1. Case study of Huangpu

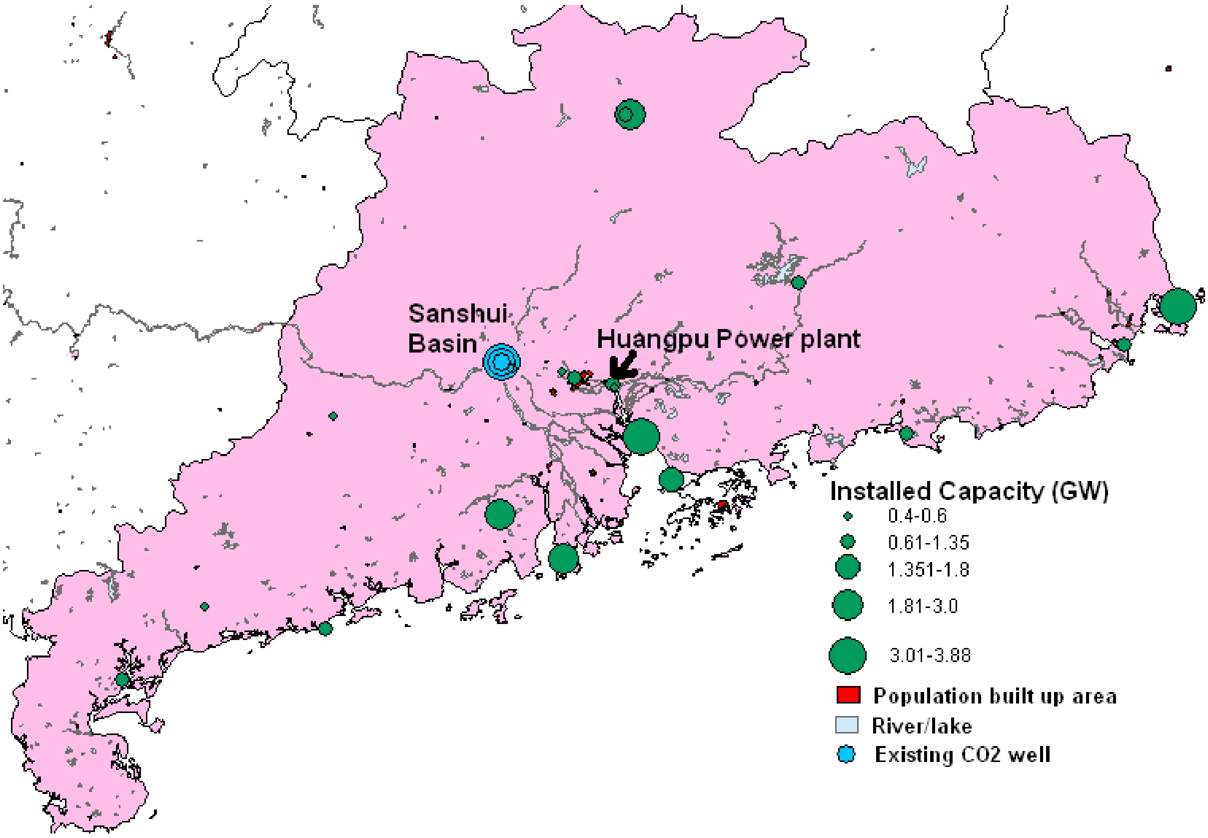

Figure 6-13 Location of Sanshui Basin and Huangpu Power plant

Based on a possible real world case in Guangdong, a potential capture route is being created using historical data, face-to-face interviews, and field studies at the Huangpu power plant in the Sanshui Basin. There are currently two power plants in operation in that area and because of the policy of replacing small size power plants with bigger ones, a new 600MW coal-fired plant will be build along the Pearl River. Huangpu power plant is 70km away from Sanshui Basin. The site selection is based on the method discussed in the previous section. The location of the basin and the power plant are shown in Figure 6-13. As can be seen from the figure, the black dotted points are cities with higher populations[24]. Consequently land is expensive, and it is very difficult to build a pipeline to link directly the emissions source and sink.

A possible early demonstration opportunity would be to transport the carbon dioxide through pipelines to the Sanshui basin using the existing infrastructure. This study estimates the pipeline route to be the same as the natural gas pipeline, which are sub branches for transporting the natural gas from west part of China to east part of China. As the natural gas pipeline is already in place, gaining pipeline access to this storage site will be less difficult compared to finding a completely new route. The total distance for the pipeline is 115.08 km accordingly (as shown in Figure 6-14).

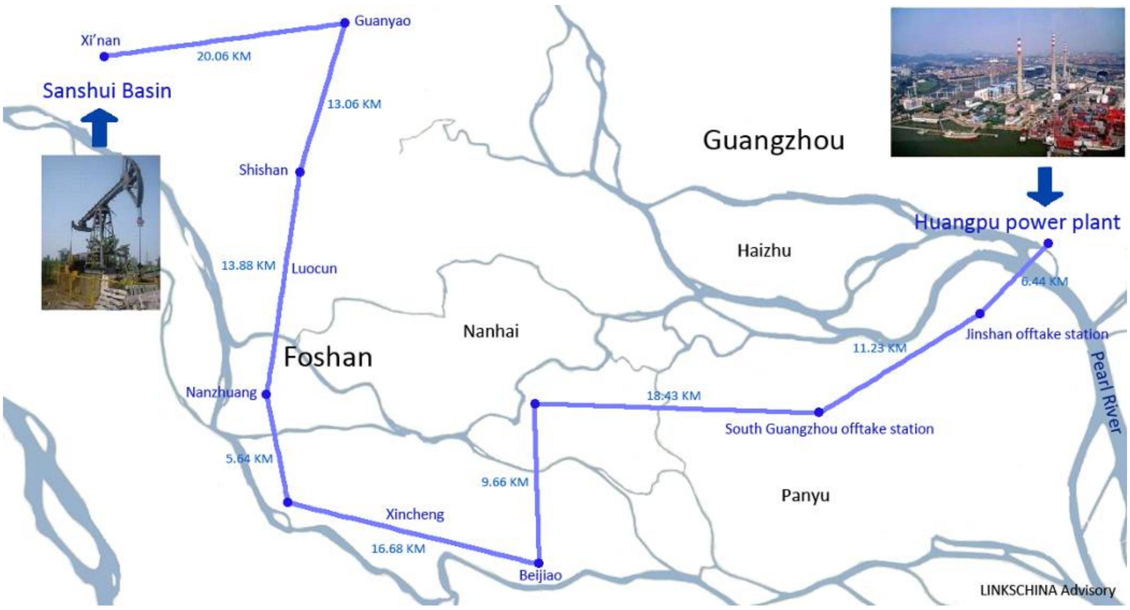

Figure 6-14 Location of Huangpu power plants (photo shown on the right), Sanshui basin (photo shown on the left) and potential route of CO2 pipeline (Liang, Reiner et al. 2009)

[24] The data is comes from the fourth national population survey in early 1990s. The fifth population survey has still not finished at the end of 2010.

2. Long term Planning

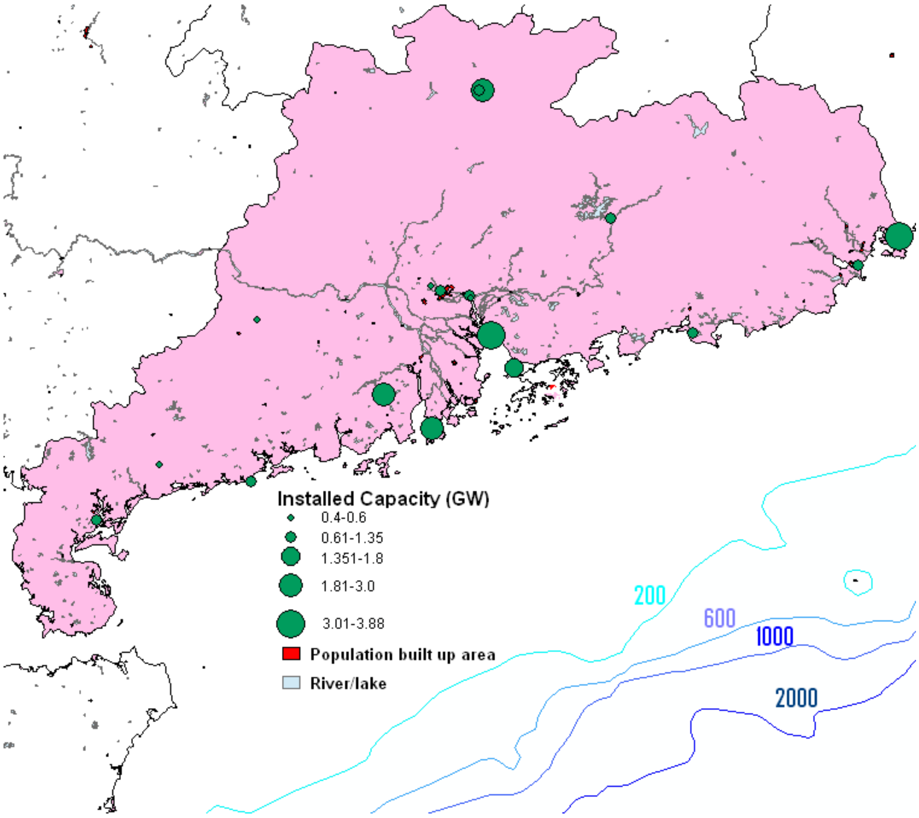

Figure 6-15 Depth of seabed (in metre)

Compared with the limited storage capacity onshore, offshore storage in saline aquifers shows a promising future for carbon capture and storage in Guangdong. Over 98% of the potential storage sites are offshore and within the easy reach of the coast. The southern part of the Pearl River basin is around 200m in depth as shown in Figure 6-15. The long term large scale storage of carbon dioxide is likely to be in saline aquifers offshore, roughly within 150 km of the coastline. For power plants built next to the coast line, the cost benefit will be bigger. In addition, such new power plants can avoid residential areas and can use sea water cooling, which is common practice in coastal power plants.

Site selection, might also be influenced and simplified by the concept of industrial development clusters. Examples of such clusters would be power plants, chemical industries and wind farm manufacturing facilities to be built in the Zhangjiang area, the new power plant in planning in the Shantou area. Both areas are close to storage sites and already have large carbon emissions. Therefore, three clusters are identified in the study as shown in Figure 6-16.

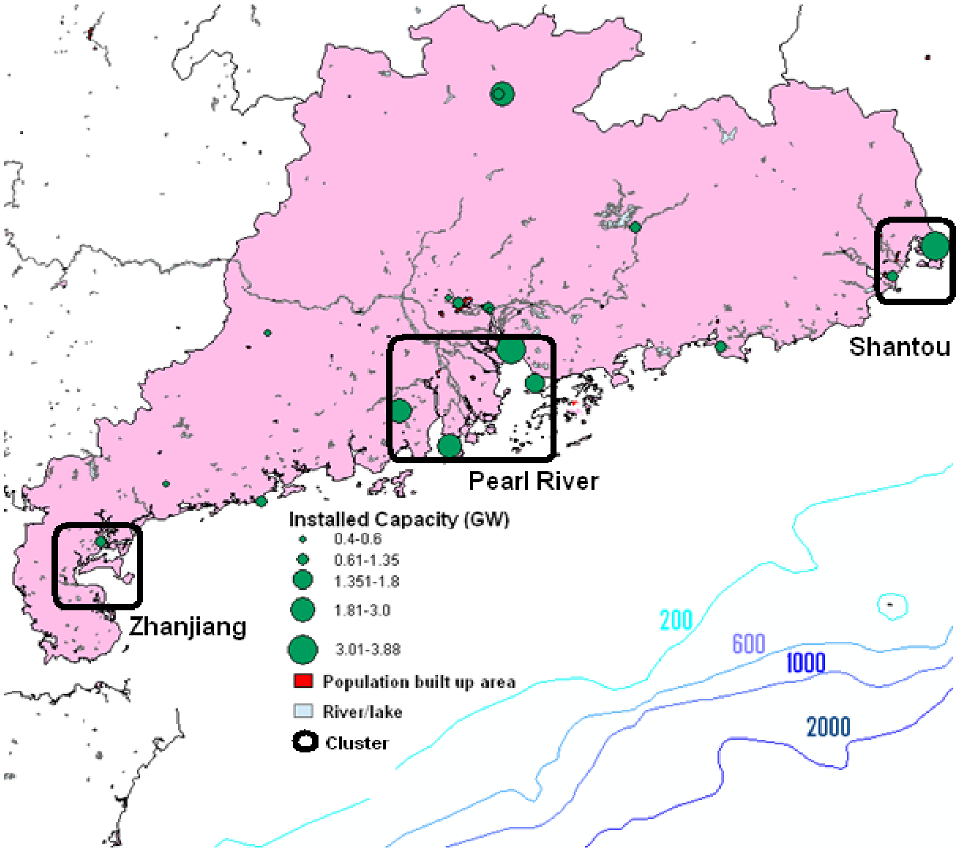

Figure 6-16 CCS clusters in Guangdong

The biggest cluster, the Pearl River cluster, has a higher installed capacity of around 15GW, compared to the clusters in Shantou and Zhanjiang, which currently have 5GW and 1.2GW installed capacity respectively. However, because of the economic development imbalance in previous years, Shantou has in recent years proposed more new power plants than elsewhere in Guangdong. The two main limitations of the cluster plan are:

A) The region can extend to a larger area, including the Bebuwan basin in Guangxi province and another large emission area in Fujian Province. Hong Kong, which is to the south of the Pearl River, hosts one of the world's largest power plants and could also be included.
B) Small scale power plants not connected to the national grid can be considered in future study. There are currently 162 units with a total installed capacity of 3.07GW. The biggest unit has a capacity of 350MW while the smallest unit is only 0.8MW (NDRC 2008). Because it does not supply electricity to the national grid, neither the

policy of the closing down small, inefficient power plant, nor SO_2 emission limitations, apply

When considering the regional extent, multi-province consideration is better than only considering a single province. As can be observed, the Zhanjiang and Shantou clusters are both located close to the bounder of Guangdong Province. Both Guangxi province and Fujian province are expected to have fast economic growth within the next ten to twenty years as labour and operational costs in Guangdong are getting higher and Guangdong province is seeking opportunities to transform its economy to high value industries rather than manufacturing.

The large number of small installed units in Guangdong has created great difficulty in the cluster planning. Since the plants do not rely on selling electricity to the national grid as their only income they are difficult to regulate by means of most of the existing environment laws. Even if a company is prepared voluntarily to cut its emissions, there remain concerns over potential bankruptcy or the effect on the company's valuation by a third party. Finally, connecting pipelines to small units might not be seen as priority compared to other emission sources. Therefore, the inclusion of small plants should not be considered as reasonable direction of investigation unless large scale retrofit happens.

The geographical location of Guangdong provides it with the opportunity to access energy sources by shipping rather than rail. Most of the coal burned in coastal areas in China is from Australia, while the inland areas largely rely on coal produced in Shanxi province or Inner Mongolia. The same principle can apply to the storage clusters. The cluster does not need to occupy any existing industrial land, it could be build on an island, which is similar to the concept of the existing power plants and LNG terminals in the region. This can save the cost of land purchase while avoiding the populated areas.

6.5 Conclusion

The site selection methodology is set out based on the experience and research on retrofitting existing power plants in China, which includes legislation, engineering, and external factors. A check list that can be easily used by engineers or investors is given in this chapter. A first of a kind spider chart is also proposed to compare the possible sites for building a capture ready plant.

Regional planning is a priority if capture ready is going to happen within the next 10 years. The concept of “region” should not be limited to a single province or country, but could include places with similar energy resources, linked electricity generating systems, and, most importantly, sharing the same storage infrastructure for CCS. In this section, the example was given in order to gain a better understanding of how clusters should be planned and created. The real challenge in planning for CCR lies in the quantity and quality of data available for a specified region, the scope for coordination beyond political borders and understanding the future development planning. Making a region carbon capture ready is not just a technical or engineering problem; it depends on planning, policy and economic issues as well.

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Chapter 7 Chinese Stakeholders' Perceptions on Capture Ready

This chapter is based on a paper submitted to the International Journal of Greenhouse Gas Control (Li, 2010)

7.1 Objectives of the survey

Globally a number of studies have been conducted to investigate the engineering requirements of carbon dioxide capture readiness (CCR) (IEA GHG, 2007; IChem, 2007; Lucquiaud and Gibbins, 2009), its political feasibility (SCCS, 2008; Markusson and Haszeldine, 2008) and techno-economic aspects (Bohm, 2006; Liang et al, 2009). Studies have apparently not been undertaken, however, to explore stakeholders' acceptance of implementing CCR. This section of the thesis builds on the CO_2 capture ready study by IEA GHG (2007) and on general perceptions on CCR obtained from a stakeholders' consultation for the NZEC project (Reiner and Liang, 2009). The aim is to understand the engineering and economic drivers and barriers to implementing CO_2 capture ready design concepts on new build coal-fired power plants in China.

The importance of carbon capture and the technical barriers of such technology have been discussed in the previous chapters. However, the acceptance and understanding of the issues mentioned above remains unknown. A survey with the objective of understanding the following issues was designed to examine the perceptions of Chinese engineers on capture readiness:

a. Understand stakeholders' willingness to make fossil fuel power plants capture ready
b. Identify the key engineering factors cited by interviewees which potentially affect the capture ready design
c. Understand the cost performance expectation from stakeholders

This first of its kind survey on carbon capture ready issues in China provides information on a range of aspects of CCR implementation that are of relevance to policy makers, power plant investors, and engineers. The format and methodology of the survey could form the basis for further work on this area in the run up to the possible introduction of CCR in China.

7.2 Methodology and demographic information

7.2.1 Data collection and sample selection

The format of the study builds on the stakeholders' communication for the NZEC study which used an online survey and follow-up face-to-face interviews (Reiner and Liang, 2009). In this research, data is primarily collected from an online survey. Subsequently two follow-up engineers' focus group discussions were carried out at two proposed new supercritical power plants[25]. The aim was to explore in detail the actual drivers and barriers to the immediate implementation of CCR. Though the opinions from a survey may not lead to actual actions, either positive or negative, (Maline et al, 2010) there is a need to understand the problems that would influence actual outcomes.

The two criteria for selecting audiences for communication through the study are (i) 'influential for others' and/or (ii) 'project specific', based on four categories suggested by Ashworth et al (2010). In other words, stakeholders involved must have a large impact on CCS development in China or influence whether or not a specific potential power plant would have a CCR design. The target sample included 85 people[26], a majority coming from industry such as power companies (29), power design institutes (12), petro/chemical companies (11) and thermal/chemical engineering academics (5); 8 stakeholders are serving in power plant authorisation bodies, environmental approval or monitoring positions at national governments (NDRC or SEPA); 20 stakeholders are working in energy project approval/regulatory positions in local governments. In terms of geographical locations, more than one third of stakeholders (29) are working in Guangdong province and a quarter of them (22) are working in Beijing.

7.2.2 Questionnaire design and distribution

Taking advantage of the flexibility of an online survey, the questionnaire was designed to be path-dependent. Each stakeholder answered 16 common questions followed by another 4 to 7 characteristic questions from a bank of 15 questions. In designing the questionnaire the structure and format of previous CCS stakeholders' survey in China (Reiner et al, 2007; Reiner and Liang 2009) was first reviewed, as well as CCS stakeholder communication in Europe (Shackley et al, 2007). However, in contrast to previous studies, the main purpose

[25] Both plants are in Guangdong, scheduled be built before 2012 and near potential storage sites.

[26] Three stakeholders' emails did not go through and they could not be contacted for alternative emails.

this questionnaire was to understand stakeholders' ideas and concerns for implementing CCR immediately, rather than CCS at some stage in the future. A number of 'what if' questions were therefore posed, such as 'will you accept CCR, if it incurs an additional 1% fixed capital expenditure'.

As a final stage in its preparation, the online questionnaire was tested by six people, three CCS experts and three Chinese stakeholders not involved in the sample. The questionnaire was then revised according to the feedback received before being translated into Chinese and distributed to stakeholders via email. A total of 82 invitations were sent successfully on 1 Feb 2010.

In each email, stakeholders were told that an attractive token would be awarded by post after the study. At the beginning of the online survey, stakeholders were presented with the following simple description of CO_2 capture ready[27]:

At the request of the Gleneagles G8 summit (G8, 2005), the IEA Greenhouse Gas (2007) Programme published a study which identified the following key elements for CCR power plants:

- *A CO_2 capture ready power plant is a plant which can include CO_2 capture when the necessary regulatory or economic drivers are in place. The aim of building plants that are capture ready is to reduce the risk of stranded assets and carbon lock-in.*
- *Developers of capture ready plants should take responsibility for ensuring that all known factors in their control that would prevent installation and operation of CO_2 capture have been identified and eliminated. This might include:*
    - *A study of options for CO_2 captures retrofit and potential pre-investments*
    - *Inclusion of sufficient space and access for the additional facilities*
    - *Identification of reasonable routes to storage of CO_2*
- *Competent authorities involved in permitting power plants should be provided with sufficient information to be able to judge whether the developer has met these criteria.*

[27] Questionnaire is available at http://www.captureready.com/EN/Channels/Survey/showDetail_Step_1.asp?ClassID=1&VoteID=5&VoteType=2 also at Appendix 5. The IEA GHG study referred to is (IEA GHG, 2007).

7.2.3 Focus Group Discussions

The two focus group meetings were held at power companies located in Foshan and Guangzhou respectively, both in Guangdong province. There were two purposes for holding the group discussions:

- To understand the reasons behind stakeholders' preferences in the online survey;
- To investigate drivers and barriers to immediate deployment of CCR in their new plants.

In the focus group meetings stakeholders were given a Chinese translation (IEA, 2007) of the CO_2 capture ready power plant report by IEA GHG (2007). Each focus-group discussion started by investigating how well the current plant design for the new supercritical power plant in question would meet the engineering and geographical requirements in the report. Each discussion lasted about 3 hours.

7.2.4 Data analysis

Online survey data obtained was analysed using qualitative and quantitative methods. Descriptive analysis was first applied to determine how responses were distributed among different categories, and the average degree of acceptance. Regression analysis was then undertaken to investigate relationships between variables, for example exploring factors that might affect a respondent's general attitude towards CCR. Qualitative data was also obtained from notes and observations in the focus group meetings. In order to gain an insight from these meetings the method of narrative summary analysis and interpretation (Mishler, 1986; Labov, 1997) was adopted. In addition, survey results with previous stakeholders' communication in China and Europe were also compared.

7.2.5 Demographic information

A total of 31 comprehensive responses[28] were received by the end of February, an overall response rate of 38%. The rate was lower than for the previous NZEC online survey (51%), perhaps because the stakeholders were generally less confident in answering the more technical survey questions. However, a satisfactory number of responses were received from each sector and the sector composition of responses was thus very close to the initial desired structure[29] (Table 7-1). The locations of respondents were distributed over 6

[28] Two respondents who didn't finish the all questions are excluded in the database of respondents.
[29] The invitation of attend the survey was send out based on the background of the interviewee.

provinces, with the greatest number (13) working in Guangdong, followed by 7 located in Beijing.

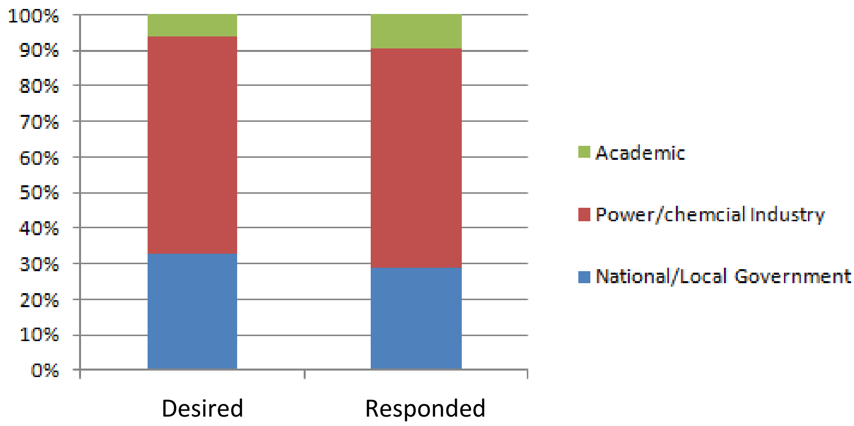

Figure 7-1 Distribution of sample versus responded by type of institution

Three government respondents come from national institutions while six are working at local authorities. When industry and academic participants were asked for their areas of expertise, nearly half selected 'power engineering' (11) and four people 'management' (Figure 7-2).

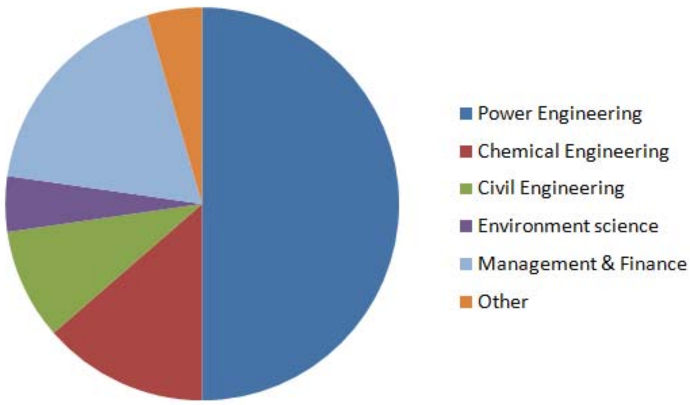

Figure 7-2 Distribution of industry and academic responded by claimed expertise area

On average, stakeholders estimated they spent 85% of their working time on energy issues, 24% on climate change related issues and 4% of their time on CO_2 capture and storage. The results show a great majority of the respondents are not inside the CCS community. However, every stakeholder stated they had heard of CCS before this survey and a majority (55%) said they had come across the term CCR in Chinese as well. In follow-up interviews, four out of six stakeholders stated they had heard of the English term 'CCR' before the online survey.

7.3 Results

7.3.1 General views on climate change and CCS

There are almost equal numbers of optimistic and pessimistic responses on whether or not current global climate policies can significantly reduce global carbon emissions in the next decade. An interesting finding from regression analysis was that stakeholders spending a greater percentage of their working time on climate change tended to believe that with current global climate policies it would be 'difficult' to reduce global carbon emissions[30].

Overall, slightly more than half of the stakeholders view CO_2 capture and storage as 'necessary' or 'very necessary' in order to achieve deep greenhouse gas emission reductions. Industry stakeholders are less supportive of CCS, consistent with observations in an earlier NZEC[31] study (Reiner and Liang, 2009). Stakeholders spending more time on climate change are more likely to prioritise CCS in achieve deep cuts in global carbon emissions[32].

To assess their expectations regarding which capture and storage technologies will be deployed in China, stakeholders were asked their views on the expected prevalence of different capture technologies in the first 10 and the first 100 coal-based CCS projects respectively. As illustrated in Table 7-1, in the first 10 CCS projects, post-combustion capture was thought to be 13% and 23% more probable than pre-combustion capture in IGCC or polygeneration, coal-to-liquids (CTL) and refinery plants. With respect to the first 100 projects, the preference of pre-combustion capture at IGCC and poly-generation plants is very close to post-combustion. The result also proved the early assumption in the thesis that post-combustion capture on pulverised coal plants will be the dominant market player as CCS is coming into force due to its popularity and easy handing among the power companies, as explained in chapter 2. During follow-up interviews, an engineer from a power company suggested that Chinese companies were confident about building and

[30] At 99% confidence level, as shown in Table A.1 in Appendix 4
[31] The focus of the NZEC study and STRACO2 study is on CCS , not carbon capture ready
[32] At 95% confidence level, as shown in Table A.2 in Appendix 4

operating conventional pulverised coal-fired power plant and therefore IGCC or polygeneration could hardly play a key role in the next 10 years. Another engineer argued that CO_2 at chemical plants should take priority for capture due to its higher partial pressure and the operators' better knowledge of separating CO_2 streams. Half of the participants in the focus group discussions had not heard of oxyfuel. A majority of engineers at focus group discussions believed all major capture technologies would be demonstrated and mature after the first 100 coal-based CCS projects in China.

Table 7-1 Stakeholders' expectations for those capture and storage technologies that would be most used for the first 10 and 100 coal-based CCS projects in China

	First 10 projects	First 100 projects
Capture technologies		
Post-combustion capture	68%	97%
Pre-combustion capture in IGCC	55%	94%
Capture at polygeneration, coal to liquid or chemical plants	45%	87%
Oxyfuel	16%	23%
Unsure	3%	3%
Storage technologies		
Enhanced oil recovery	77%	84%
Depleted oil or gas reservoir	68%	81%
Geological storage in saline aquifer	39%	48%
Enhanced coal bed methane recovery[33]	87%	90%
Unsure	10%	10%

Regarding storage technologies, as in previous studies in the STRACO2 (2009) and NZEC projects (Reiner and Liang, 2009), stakeholders are more in favour of EOR (enhanced oil recovery) and ECBM (enhanced coal bed methane) than aquifer storage. During follow-up group discussions, five out of six stakeholders selected both EOR and ECBM for the first 10 as well as the first 100 projects. However, all of them had no idea of the limited capacity in China to store CO_2 in oil/gas fields or coal seams. This restriction was explained in more

[33] Stakeholders are described that coal seam may not be minable once CO_2 is injected

detail, by presenting the Chinese summary of CCS special report by IPCC (2005), but their attention and logic concentrated on how much a tonne of CO_2 could be sold for to oil companies, brewing or other industrial users. Unsurprisingly, stakeholders select a wider range of capture of technology options when the assumption is expanded from 10 to 100 projects. But those selecting saline aquifers as the primary storage method for the first 100 large-scale projects in China remains at less than half, perhaps as a result of limited understanding of storage technologies and CO_2 storage capacity because the stakeholders are mainly from non-geological backgrounds.

7.3.2 Perceptions and technical concerns related to CCR

When asked their general perspectives on designing a plant to be CO_2 capture ready, more than half of the stakeholders expressed either 'strong support' or 'support' (Figure 7-3). In a follow-up group discussion, a power plant manager stated a belief that removing CO_2 would certainly be the next environmental requirement after deNOx and deSOx. It was also found that those spending more time on climate change are more likely to have supportive attitudes to CCR[34], similarly those spending more time on CCS[35]. Interestingly, stakeholders prioritising CCS as an important technology are not more likely to support CCR[36].

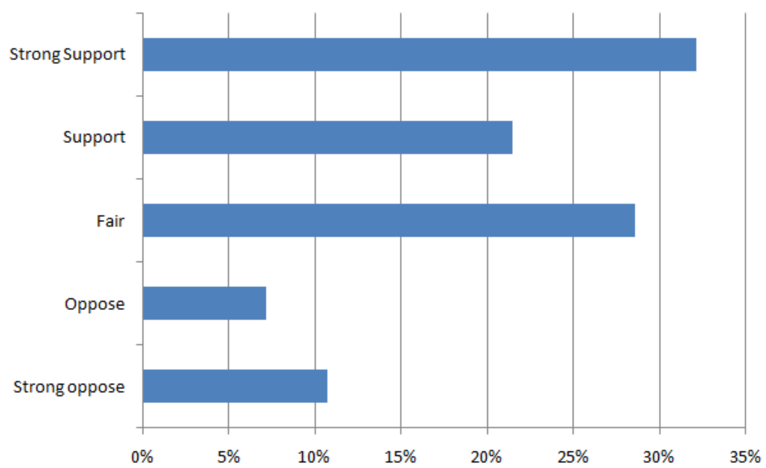

Figure 7-3 Stakeholders' general perceptions of CO_2 capture ready[37]

[34] At 95% confidence level, as shown in Table A.3 in Appendix 4
[35] At 95% confidence level, as shown in Table A.4 in Appendix 4
[36] as shown in Table A.5 in Appendix 4
[37] Each stakeholder is given a brief description of CCR at the beginning of the study; 3 stakeholders select 'unsure'

To gain insights into the potential benefits of CCR for China, participants were given four statements, which were also provided to stakeholders in the NZEC survey but with CCS demonstration instead of CCR: ‘Add credit to Chinese government in climate area’ (3.7) and ‘Attract foreign investment’ (3.5) received higher scores than ‘Benefit Chinese CCS equipment manufacturers’ (2.9) and ‘Benefit Chinese energy firms investing in CCS technologies’ (3.1). The results show a difference with respect to the perceived benefits of demonstration in the earlier study, where ‘Create advantage for Chinese energy companies to invest in CCS’ gained the highest acceptance. During the follow-up dialogue with stakeholders, it was found that local power companies, though very interested in the technologies, are not confident in investing in CCS due to lack of policy support and available equipment.

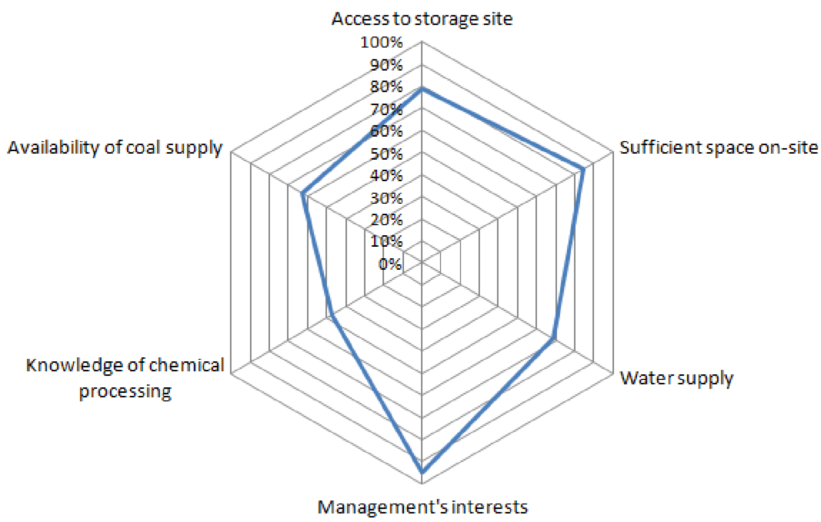

Figure 7-4 Stakeholders’ views on the relative influence of factors affecting CO_2 capture ready decisions at individual power generation projects in China

Industry stakeholders were asked to identify the most critical technical factors influencing CCR decisions for individual projects (Figure 7-4). More than 90% of respondents believed a key factor is to gain ‘Management’s interest’ on CCR. ‘Sufficient space on-site’ and ‘Access to storage site’ also received more than 80% acceptance. Half of the stakeholders were not concerned about the lack of chemical engineering experience in electricity utility companies. During follow-up group meetings it was stated that power companies normally had a few experienced chemical engineers, working on water or flue gas treatment, and they expressed strong interest and confidence in the companies’ ability to operate CO_2 capture equipment. In addition to water supply issues, they also asked about the amount of waste water from CO_2 removal processes, because a lot of new power plants in Guangdong are not allowed to discharge waste water into rivers and so waste water must be evaporated by a rather expensive process on-site after which waste chemicals and the dehydrated residue from the waste water are disposed of at special landfill sites. Stakeholders were also highly concerned about the efficiency penalty after retrofitting capture and the transportation of CO_2 to storage sites.

For participants prioritising ‘sufficient space on-site’ and ‘water supply’, follow-up questions to quantify the acceptance of the issues were asked in online survey. More than 50% respondents believed ‘1/8 to 1/4 the size of the power plant’ (2*600MW plant is used as baseline) is the reasonable extra space to host the capture unit and around 30% selected ‘not sure’ while most believed extra water consumption should ideally not exceed 1/8 of the water requirement (in water-constrained locations) of the original plant for a capture retrofit. The result has shown that stakeholders might not be ready for the 100% capture at the moment. As discussed in chapter 6, the total amount of land required is similar to the size of the power generation unit, while 1/8 to 1/4 the size of the power plant is smaller than the total generation unit for a power plant. However, this point was not made clear for the stakeholders at the time of the survey. As the partial capture solution has not been considered when conducting the survey, if this the desirable case for capture in China, then the energy penalty and cost changes could refer to the 50% capture case in the ASPEN simulation. Because the amount of carbon dioxide captured per kWh of electricity produced from coal is similar to the amount from 90% capture at natural gas power plants (and emissions are similar to unabated natural gas power plants), this opinion could help policy makers when drawing up new regulations for different power generation technologies.

In the follow-up group meetings, it was found that some stakeholders would consider reserving more extra space (than expected to be required by the capture facilities) in the hope that a new generation unit could also be permitted in the future. But if no extra unit could be permitted, the capture unit should occupy as little space as possible. The extra water consumption was also considered likely to be a problem, but only in water shortage regions. If power plants are built along rivers, or have easy access to them, the ready availability of water, and hence better cooling, could therefore be factor that will reduce the subsequent cost of adding capture to a CCR plant

The survey asked which institutions would be considered as the most appropriate to suggest suitable locations to build CCR coal-fired power plants in China. There was no consensus among industrial respondents based on the results of the online survey. A majority (58%) would select power companies, national government and local governments. Oil and gas companies, who have geological information, were, however, not prioritised by 80% of respondents.

7.3.3. Preferences of Regulatory and Potential Financial Schemes for CCR

There were no consistent views by government officials on strategies to incentivise CCR in the next 10 years (2010-2020). ‘Support from foreign public institutions’ (44%) and ‘Market based incentives’ (33%) were believed to be more desirable than ‘Policy mandate for new plants to retrofit capture by a certain date’ (22%) and ‘Provide direct financial subsidy on CCR investment’ (0%). Generally, Chinese government officials probably considered it was still too early to use financial or political resources to accelerate the implementation of CCR.

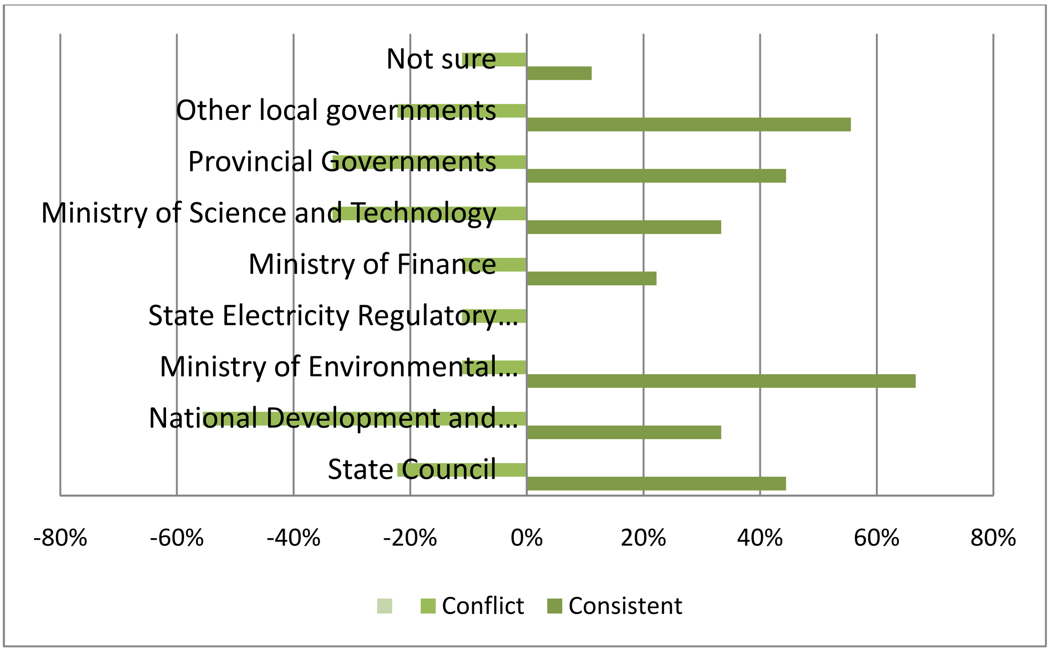

Figure 7-5 Government stakeholders’ views on the relationships between Implementing CCR and objectives of different departments[38]

[38] The National Energy Bureau is regarded as part of the NDRC or the State Council in this study

It is critical to understand the views and attitudes of Chinese government departments towards CCR, especially because Chinese energy and environment related government departments have frequently adopted new functions and evolved their structures rapidly over the last ten years (Liang et al, 2008). Government officials were invited to point out whether CCR complies or conflicts with different departments' objectives. The result reveals that most stakeholders agreed deploying CCR benefits the Ministry of Environment Protection (Figure 7-5), probably because it potentially strengthens its regulatory and monitoring capacity. There are divergent views on whether implementing CCR would be consistent or conflict with the objectives of the two major national energy policymaking departments, the NDRC and the State Council. This could be explained by the complex policy objectives in NDRC and State Council, for example, the target of reducing GDP energy intensity may discourage increasing fuel consumption to capture CO_2, but the Chinese carbon intensity target may encourage deployment of CCS. A majority of stakeholders believed that local governments would benefit from implementing CCR.

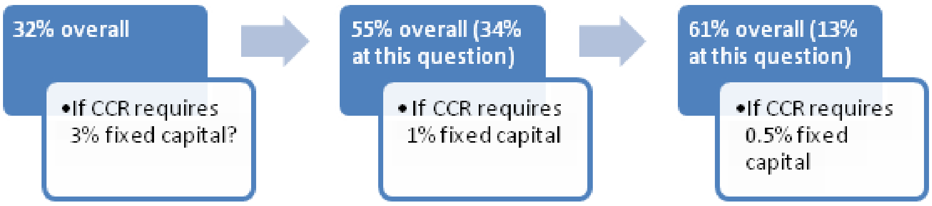

Figure 7-6 Responses to questions on the acceptable costs of CCR in China

With regard to willingness to pay to implement CCR, a third of stakeholders said they would be prepared to pay up to 3% on the plant capital cost[39], more than half agreed to 1% and 60% agree 0.5%. An earlier finding by Reiner and Liang (2009), that power industry stakeholders are more reluctant to accept the extra fixed capital cost, was confirmed, with only 44% acceptance on 1% extra fixed capital cost and 17% acceptance on 3%. The overall acceptance is also weaker than findings in the NZEC study where 58% of industry stakeholders were willing to pay an additional 1%. This discrepancy could be due to the different order of the questions: in this study they started with a higher cost assumption,

[39] The rationale of 3% is based on the estimation of IEA GHG study on CCR essential design with a clutched low pressure turbine, which is 2.89%

3%, while the previous study started with 1% as an example, and then 0.5% or 2% depending on the response (Figure 7-6).

Finally, those responses supporting CCR advocated as priorities 'Provide incentive for land reservation for on-site for capture unit' (1.9[40]) and 'Consider access to CO_2 storage site' (2.1) as priorities. In group discussions, it was considered that both (non-CCR) plants that were investigated would have very limited space for future full scale retrofit. Managers from both plants complained that there were currently very strict controls on land use for thermal power plants in China.

7.4 Conclusions

CCS is a well established concept to decarbonise coal-fired electricity generation in China. A majority of respondents expressed interest or supportive attitudes towards CCS and CCR, especially those stakeholders spending more time on climate change and/or CCS. With respect to technology preferences, post-combustion technology was thought to be more likely to be used than pre-combustion IGCC or pre-combustion polygeneration in the first 10 projects in China. Most interviewees are focussed on utilization of CO_2 captured from power plants rather than simple storage underground. Thus EOR and ECBM are commonly viewed as the most likely storage options for the first 10 and for the first 100 projects, while those respondents who expect significant amounts of saline aquifer injection amounted to less than half of the sample. It should be noted, though, that the majority of the industry stakeholders are engineers with limited experience related to potential CO_2 storage activities.

Stakeholders strongly believed a benefit of CCR is that it could attract additional foreign investment to capture CO_2 in a plant's life time, in contrast with an earlier study finding that relatively few agreed CCS demonstration projects could attract foreign investment. It seems stakeholders believed foreign investment should be used to support the capture and storage elements of a project but is not necessary at the base power plants. The positive effect of CCR on the Chinese government's international credit for combating climate change is also selected as an outstanding benefit.

[40] 1 is strongly agreed, 3 is neutral and 5 is strongly disagree.

To implement CCR in China, it is urgent to influence project management as well as senior government officials, with 90% of stakeholders from industry considering this factor critical. Besides making sufficient space on-site and considering access to storage sites from plant locations it is also necessary to investigate local plant design conventions and regulations, such as water constraints and cooling technology. There is no clear signal as to which government departments may have the strongest interest in CCR, but most of the government officials in this study believed implementing CCR would be consistent with the objectives of Ministry of Environmental Protection. More than half of the stakeholders perceived that 1% extra cost for CCR would be acceptable, consistent with a previous study in the NZEC project (Reiner and Liang, 2009), but government officials believed that market based mechanism or foreign support would be the key driver for CCR from 2010 to 2020.

Partial capture should be considered rather than full capture in a capture ready plant. As most power plant operators are more willing to spare part of the power plant site for capture ready design, while interest is not significant for full capture at the moment. If a 50% capture ratio is defined, the amount of carbon dioxide captured per kWh of electricity produced from coal is similar to the amount from 90% capture at natural gas power plants.

Given the existing awareness of CCR and the sub-issues involved in its implementation it would probably be feasible to implement a regular and effective communication framework (Liang and Li, 2010) to further explore and address stakeholders' concerns, including through links to the development of CCR expertise and experience elsewhere (such as in the UK, where CCR is now a requirement for new power plant permitting (DECC, 2009). Such a programme has the potential to help accelerate the implementation of CO_2 capture ready designs for new Chinese coal-fired power plants.

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Chapter 8 Conclusions

The use of fossil fuel in primary energy supply is predicted to increase in the next two decades (IEA, 2009). In China, a large number of new coal-fired power plants are being constructed and it is estimated that coal will still supply over 60% of primary energy in China in 2020 (CEC 2009, IEA 2009). CO_2 capture and storage (CCS) is therefore a promising technology option to decarbonise the Chinese energy sector while at the same time satisfying its fast growing energy demand (Liu and Gallaher, 2010). Making new Chinese coal-fired power plants CO_2 capture ready could greatly facilitate their subsequent retrofitting to capture CO_2 and can significantly reduce the probability of 'carbon lock-in' for the whole of their lifetime (Liang et al, 2009).

During the course of this study, a number of results have been found including:

8.1.1 CCS and CCR for gasification process

The possibility of capturing carbon dioxide through the gasification process in China was predicted to have a promising future (Chen and Xu 2010). In this study, an investigation of the Chinese gasification industry showed that the potential for capturing carbon from gasification plant using coal as feedstock varies according to the plant's end products. Although a number of IGCC plants have been proposed in China, at the time of writing only one plant has obtained construction permission from NDRC (Greengen 2009). Some of the other proposed IGCC plants have included a future extension of their plans to capture CO_2 by post-combustion technology at a later stage. But with the main IGCC plant's future still uncertain, the later retrofit stage may not be realistic.

Existing studies comparing the up-front spending in IGCC plants and the cost saving after retrofit shows that capture ready for IGCC plant is not an economic and technically favourable investment, because of the difficulty in matching the turbine before and after capture. If an IGCC plant investor is planning to build a carbon capture plant in the future, the proposed plant should be built as a pre-combustion capture facility from the beginning rather than be retrofitted at a later stage.

Most of the new advanced gasifiers in China are ordered by Coal to Liquid (CTL) companies, and the appropriate capture ready design for such companies will vary based on the process and liquid end product. Capture ready is already on the agenda of a company which is constructing a direct liquefaction technology plant in China (at the time of writing only one direct liquefaction plant has been authorised for construction). Some indirect liquefaction plants have also been planned to add capture equipment at a later stage. Self motivation is a strong driver in the gasification industry for CTL plants in relation to carbon capture, especially to capture ready, because the worry of the additional capture requirement in the future. Because of the high concentration and (or) high pressure of carbon dioxide in some of the streams in the CTL plants, the overall capture cost could be slightly cheaper than carbon capture from conventional power plants.

8.1.2 Power plant carbon retrofit potential in China

If carbon capture and storage becomes mandatory in China some early cheap opportunities exist in the gasification industry. However, conventional pulverised coal (PC) fired power plant remains the largest carbon dioxide emitter in the energy sector (CEC 2009). Recent orders from boiler companies and other estimates by international organisations have shown that the growth in the PC industry is likely to continue over the next decades. The current Chinese policy on “increasing energy efficiency” and “closing small inefficient units” caused the industry to accelerate the change to even bigger power generation units and advanced boilers in China. Power plants with 1000MW, 660MW and 600MW units will dominate the market in the future. Consequently the next part of the study turns the focus onto the PC industry.

In order to understand the current power plant industry and the potential for CCS in China, a screening study on Chinese large size power plants was carried out using Google Earth. The clear Google images of the layouts of 75 power plants have revealed that around 50% of the existing power plants studied will be difficult to retrofit and may cause carbon lock-in in the future. This is especially true for power plants that were built relatively early in more developed areas. It will be relatively easy for some of the plants studied to be partially (as opposed to fully) retrofitted because of the tight layout of the existing generation units. In this type of plant, the units that are built at the end of a row of units (if plants are built parallel to each other) can be more easily retrofitted without changing the layout of the plant too much.

8.1.3 ASPEN modelling results

An ASPEN simulation model, designed to estimate the potential changes for advanced PC plant, can be used to demonstrate possible changes that might be involved in a retrofit case. The 1000MW ultra supercritical power plant at Zhouxian, Shandong province was selected as the baseline plant, because of the large market potential for large size generation units in China. The boiler unit is one of the most common types of its scale; its general operation conditions are modelled. The retrofitted system combines the conventional power generation unit, the additional post-combustion unit and additional associated equipment. In this model, the efficiency drop is estimated to be around 8.6% after retrofit for a 90% capture (or 6% for a 50% capture). This simple model gives power plant owners an uncomplicated way to examine their own plant for carbon capture. A list of the equipment needed for the retrofit is also summarised for plant operators.

8.1.4 Capture ready in China

Retrofitting existing power plants is only one important issue to be explored in China. Planning new power plant to fit in the existing power network is another crucial challenge. Building power plants with a carbon capture ready design can help ease the problem. Firstly, site selection methodology for capture ready power plant is set out, including legislation, engineering, and external factors. The criteria used for assessing the capture ready site are provided in a checklist. When a number of sites are selected as possible candidates a spider chart can be used to rank the scoring for each site and help to make the final investment decision.

Geographically China is a large country. The differences in economic development, geological formations, eco systems and natural resources make it very hard for China to plan capture ready power plant. To simplify the problem, a regional planning (as opposed to national planning) regime is recommended in China. Guangdong Province, in the south of China is selected as an example to show the analytical process. The study shows all the power plants with a least one unit over the size of 300MW in Guangdong that supply electricity to the southern grid. An analysis linking power plant located in the Pearl River delta, the early storage potential in the Sanshui basin and planned connecting transport pipelines shows the potential of CCS in Guangdong province. In conclusion, three cluster locations are proposed for future large scale off shore storage. At the moment, five organisations in south China and two partners in the UK have just started a project on "Making Guangdong the first capture ready province in China" funded by the UK Foreign and Commonwealth Office (FCO) (Captureready 2010).

8.1.5 Stakeholders' interview

Building on the capture ready and retrofit engineering study done previously, an online survey on capture ready issues in China, followed by face to face interviews, was also carried out in order to get a better understanding of power plant engineers' comments in the study results. The result found that CCS and capture ready are already relatively well established concepts among the interviewees, and post combustion capture, rather than pre-combustion capture, technology is considered more likely to be used in the first 10 demonstration projects. For the interviewees, storing carbon dioxide basically means EOR or ECBM at the moment. The stakeholders believed that capture ready is a way of attracting foreign investment and they also share the view that the additional foreign investment should be used to fund the capture unit rather than the power plant itself. The survey result also found that in order to implement capture ready, influencing the power plant project manager is as important as influencing senior government officials. They also considered access to storage sites as an important issue. More than 50% of stakeholders believed that the extra space to accommodate the capture unit should be '1/8 to 1/4 the size of the power plant' (2*600MW plant were used as baseline), but 30% still selected "not sure" in their answers. The extra water consumption for the capture unit should not exceed 1/8 of the water requirement for the original plant in water shortage areas, but this was not seen as a problem in water abundant areas.

8.1.6 Summary of findings

To summarise, the engineering requirements and strategies to implement CCS and capture ready in China have been investigated, beginning with understanding the nature of the research question, generating the results of the modelling, analysing the results, and understanding the current status. The main findings are:

1. It may not be economic to build pre-combustion capture ready for power generation in China, but suitable IGCC sites are being considered as options for post-combustion retrofit (Chapter 2)

2. There is a high possibility of carrying out capture ready in most gasification-based chemical and coal-to-liquid plants in China (Chapter 2)

3. Capture ready in china for pulverized coal plants is important and the best way to avoid carbon lock in (Chapter 3)

4. The similarity in Chinese PC plant designs was studied and possible layout planning and retrofit designs are set out (Chapter 4)

5. A simple ASPEN model for easy-to-use post combustion capture modelling was developed and tested (Chapter 5)

6. This thesis sets out a new methodology for capture ready site selection (Chapter 6)

7. It also includes GIS cluster design for Guangdong when planning future potential power plant locations (Chapter 6)

8. Finally it presents the results of a survey, carried out mainly with power plant engineers, on technical design for new CCR plants (Chapter 7)

8.2 Recommendations for policy makers

More than 70% of the power plants installed in China are thermal power plants, and these are dominated by coal-fired power plants (BP 2009). The IEA (2009) has estimated that another 300GW of coal-fired power plants will be added before 2030, by which time 60% of China's electricity will be produced from coal. In order to reduce the total greenhouse gas emissions from the electricity sector in China, carbon capture and storage technology is the only solution given the current circumstance. The technology includes two elements, capture retrofit for existing power plants and making new power plants carbon capture ready.

Retrofitting existing power plants (or closing them down) is the only way to reduce current carbon dioxide emissions from coal-fired power plants. Over 80% (in terms of installed capacity) of the coal-fired power plants that supply electricity to the national grid in China have an individual installed capacities of over 1GW (CEC 2007, CEC, 2008). If power plant retrofit becomes mandatory in the future then starting with large sites can achieve relatively greater emission cuts. Some regions also show greater potential for retrofit than others, such as regions that are closer to storage sites, have easy access to coal resource, have a population with a better understanding of climate change. For such regions, it might be beneficial to introduce the cluster concept and share some of the transport and storage infrastructure. However, a large number of power plants appear to be less attractive for retrofit from an investment point of view. Whether to retrofit or close down such plants should be decided on a case to case basis.

At the moment, there are no mandatory policies or suggested guidelines for new built power plants to be constructed in a carbon capture ready way. However, building power plants in a "ready" state is not a new concept for power plant engineers or policy makers. In the past, Chinese policy makers have seen many power plants built in a SOx ready state and currently, and currently also, in a NOx ready state, in both cases because power plant investors are aware of the environmental challenge they might face during the lifetime of the power plants. Similar to these concepts, carbon capture ready could be introduced to power plants through a bottom up process rather than a top down regulation. And the concept of partial capture should also be suggested. However, power plant investors need to be aware of such a solution before it can be rolled out nationally, as the survey in this study identified. Introducing such concepts through workshops, local unions, public or professional media is a good way of increasing awareness.

8.3 Suggestions for future research

The following section outlines some suggestions for future work in this area.

a) The Google Earth image data base should be upgraded annually, when yearly new data on the large sized plants is published by China Electricity Council (CEC). The work can help the understanding of the changes in general layout for new power plants and the technology involved (especially the cooling technology). By summarising the data and comparing the images, a better assessment of the latest plant design configurations can be generated to inform capture ready design concept developments. In addition, the trends in locations selected for new plants should be studied. For example, more plants may be being built either in coal abundant areas (aided by the very rapid development of the transmission grid) or in high electricity consumption areas. Such work will provide important data for capture ready site location planning in China, for example whether plant should built at a CO_2 storage location with good transmission grid or at an accessible site with pipeline transport.

b) Use the ASPEN simulation results based on a 600MW unit to investigate different degrees of capture for different plant operating conditions. The database of different power plant parameters could also be investigated and fed into the model. Finally, an Excel based tool could be created for such simulations to give preliminary results. The user will only need to input the boiler conditions, such as the maximum pressure and temperature for the boiler's steam flow rate, unit capacity, low pressure turbine working conditions, flue gas conditions. A list of additional equipment and its working conditions will also be required. The Excel file will then give the efficiency drop for different levels of capture. If a power plant has this tool instead of the ASPEN model, the owners can evaluate their power plant easily online, and this may help to accelerate the development of CCS.

c) Investigate the use of ammonia based solvent instead of amine based solvent in the simulation. As in the Gibbins et al (2009) study, ammonia based solvents are calculated to have a much lower energy consumption level than amine based solvents. Ammonia is a common chemical product in China, as described in Chapter 2. When ammonia is used for the capture process, carbon dioxide emission reduction could be achieved in both the gasification and electricity industry.

d) The criteria for a capture ready plant site selection and design could be analysed quantitatively. More of the criteria could be calculated through a serious of mathematic equations, instead of using qualitative methods. This might result in a reduction of individual personal biases and create a better evaluation platform.

e) The survey on CCS or capture ready should be repeated each year to show changes of opinion among stakeholders. By tracing attitude changes, policy makers can better understand the situation and concerns among industry investors.

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Appendix

Appendix 1 Statistical table for China power plants with aggregate installed capacity of 1GW and above by the end of 2006 (CEC 2007)

No.	Power Plant Name in English	Plant name in Chinese	Units(MW)	Capacity at the end of 2006 （GW)	Clear in Google[41]?
	Total of the 1000 GW capacity power stations	百万电厂合计		283.8	74
	Thermal Power Plants	其中：火电小计		233.3	107.7
1	Inner Mogolian Darlata Power Station	内蒙古大唐托克托发电公司	8×600	4.8	Y
2	Houshi Power Station, Huayang, Fujian	福建华阳后石电厂	6×600	3.6	Y
3	Power Station of Zhou County, Shandong	山东邹县电厂	2×600 4×335 1×1000	3.5	N
4	Diantai Mountain Power Station, Guohuayue, Guangdong	广东国华粤电台山电厂	5×600	3.0	N
5	Dezhou Power Station, Huaneng, Shandong	山东华能德州电厂	2×700 1×330 2×310 1×300	2.7	Y
6	Inner Mogolian Darlata Power Station	内蒙古达拉特发电厂	6×330 1×600	2.6	
7	Zhangjiakou Power Station, Datang, Hebei	河北大唐张家口发电厂	8×300	2.4	Y
8	Xibaipo Power Station Ltd, Hebei	河北西柏坡发电有限责任公司	4×300 2×600	2.4	Y
9	Wufa Mountain Power Station, Datang, Zejiang	浙江大唐乌沙山发电厂	4×600	2.4	N
10	Zeneng Power Generation Company.Ltd, Guohua, Zejiang	浙江国华浙能发电有限公司	4×600	2.4	
11	Jiahua Power Generation Company.Ltd, Zejiang	浙江嘉华发电有限公司	4×600	2.4	N
12	Nayong Power Plant, Guizhou	贵州纳雍发电总厂	8×300	2.4	N
13	Nabi Power Station, National Power Generation Company,	江苏国电谏壁发电厂	2×50 3×100 4×300 2×330	2.3	N

[41] Clear means the main location and boundary of equipments can be identified clearly.

	Jiangsu				
14	Yangcheng International Power Generation Company.Ltd, Shanxi	山西阳城国际发电有限责任公司	6×350	2.1	N
15	Luohuang Power Station, Huaneng Company, Chongqing	重庆华能珞璜电厂	4×360 1×600	2.0	Y
16	Yuhuan Power Station, Huaneng Company, Zejiang	浙江华能玉环电厂	2×1000	2.0	
17	Shaojiao C Power Station, Guangdong	广东沙角 C 电厂	3×660	2.0	Y
18	Huarun Electric Power (Changshu) Company.Ltd, Jiangsu	江苏华润电力（常熟）有限公司	3×650	2.0	N
19	Xingtai Power Station, Hebei	河北邢台发电厂	6×220 2×300	1.9	Y
20	Xiangtan Power Generation Company.Ltd, Hunan	湖南湘潭发电有限责任公司	2×25 1×50 2×300 2×600	1.9	N
21	Yangzhou No2 Power Station, Jiangsu	江苏扬州第二发电厂	2×630 1×600	1.9	Y
22	Zhenjiang Power Generation Company.Ltd, Jiangsu	江苏镇江发电有限公司	2×137.5 2×140 2×630	1.8	Y
23	Gaoqiao No2 Power Station, Outer Shanghai	上海外高桥第二发电有限公司	2×900	1.8	Y
24	Taicang Power Generation Corperation, Huaneng Company, Jiangsu	江苏华能太仓发电公司	2×300 2×600	1.8	Y
25	Beilun Power Generation Company.Ltd, Zejiang	浙江北仑发电有限公司	3×600	1.8	Y
26	Lanxi Power Generation Corperation, Zejiang Energy Company	浙能兰溪发电有限公司	3×600	1.8	Y
27	Sanmen Rapids Power Station, Datang, Henan	河南大唐三门峡发电厂	2×600 2×300	1.8	Y
28	Mawan Power Station, Guangdong	广东妈湾发电厂	6×300	1.8	
29	Guang'an Power Station, Sichuan	四川广安发电厂	4×300 1×600	1.8	N
30	Diandong Power Station the first Stage, Diannong Energy Company.Ltd, Yunan	云南滇东能源有限公司滇东电厂一期	3×600	1.8	N

31	Xuanwei Power Generation Company.Ltd, National Electric Power Company, Yunan	云南国电宣威发电有限责任公司	6×300	1.8	N
32	Huaiyin Power Station, China Energy Company, Jiangsu	江苏华能淮阴发电厂	2×220 4×330	1.8	Y
33	Qianbei Power Plant, Guizhou	贵州黔北发电总厂	4×125 4×300	1.7	N
34	Suizhong Power Generation Company.Ltd	辽宁绥中发电有限责任公司	2×800	1.6	Y
35	Ha'erbin No3 Power Station, Heilongjiang	黑龙江哈尔滨第三发电厂	2×600 2×200	1.6	N
36	Dou River Power Station, Datang, Hebei	河北大唐陡河发电厂	4×200 2×250 2×125	1.6	
37	Taicang Pot Environmental Power Generation Co.Ltd, Jiangsu	江苏太仓港环保发电有限公司	2×300 2×135 2×330	1.5	N
38	Heze Power Station, Shandong	山东菏泽发电厂	2×125 2×300 2×330	1.5	N
39	Yuanbao Mountain Power Generation Company, Inner Mogolia	内蒙古元宝山发电公司	1×300 2×600	1.5	Y
40	Taizhou Power Generation, Zejiang	浙江台州发电厂	5×135 2×330 1×132.534	1.5	Y
41	Ligang Power Station, Jiangsu	江苏利港发电厂	2×350 2×370	1.4	Y
42	Nantong Power Station, China Energy Company, Jiangsu	江苏华能南通发电厂	2×352 2×350	1.4	N
43	Dalian Power Station, China Energy Company, Liaoning	辽宁华能大连电厂	4×350	1.4	Y
44	Fuzhou Power Station, China Energy Company, Fujian	福建华能福州电厂	4×360	1.4	N
45	Huangdao Power Station, Shandong	山东黄岛发电厂	2×140 2×225 1×660	1.4	Y
46	Jiujiang Power Station, Jiangxi	江西九江发电厂	2×350 2×200 1×125 1×135	1.4	N
47	Weifang Power Station, Shandong	山东潍坊发电厂	2×330 1×670	1.3	Y
48	Yueyang Power Generation Company.Ltd, China	华能湖南岳阳发电有限责任公司	2×300 2×362.5	1.3	Y

	Energy Company, Hunan				
49	Hanfeng Power Station, Hebei	河北邯峰发电厂	2×660	1.3	Y
50	Jiaozuo Power Station, Henan	河南焦作电厂	6×220	1.3	
51	Zhuhai Power Station, Guangdong	广东珠海电厂	2×660	1.3	
52	Pucheng Power Generation Co.Ltd, Sanxi	陕西蒲城发电有限公司	4×330	1.3	N
53	Shizui Mountain Power Generation Co.Ltd, Ningxia	宁夏石嘴山发电有限公司	4×330	1.3	Y
54	Shang'an Power Station, Chian Energy Company, Hebei	河北华能上安电厂	2×300 2×350	1.3	Y
55	Qinghuang Island Power Generation Co.Ltd, Hebei	河北秦皇岛发电有限责任公司	3×300 2×200	1.3	Y
56	Xuzhou Power Generation Co.Ltd, Jiangsu	江苏徐州发电有限公司	4×125 4×200	1.3	
57	Shili Spring Power Station, Shandong	山东十里泉电厂	2×300 5×140	1.3	N
58	Xinxiang Phermal Power Station, Henan	河南新乡火电厂	2×135 1×200 1×220 2×300	1.3	N
59	Liaocheng Phermal Power Station, Shandong	山东聊城热电	1×55 1×56 2×115 2×140 2×330	1.3	N
60	Dagang Power Station, Tianjin	天津大港发电厂	4×320	1.3	Y
61	Huarun Electric Power Co.Ltd, Buyang, Anhui	安徽阜阳华润电力有限公司	2×640	1.3	N
62	Haibowan Power Station, Inner Mogolia	内蒙古海渤湾发电厂	1×600 2×330	1.3	Y
63	Xutang Power Generation Co.Ltd, Datang, Jiangsu	江苏大唐徐塘发电有限公司	2×300 2×330	1.3	Y
64	Qingdao Power Station, Shandong	山东青岛发电厂	4×300 1×25 1×23 1×12	1.3	Y
65	Shiheng Power Station, Shandong	山东石横电厂	4×315	1.3	N
66	Huaibei Power Station, Anhui	安徽淮北电厂	2×50 2×137.5 3×220 1×210	1.2	

67	Huarun Electric Power Co.Ltd, Xuzhou, Jiangsu	江苏徐州华润电力有限公司	2×300 2×320	1.2	N
68	Luo River Power Station, Anhui	安徽洛河电厂	2×320 2×300	1.2	Y
69	Canal Power Station, Shandong	山东运河电厂	4×145 2×330	1.2	N
70	Changshu Power Generation Co.Ltd, Central Electric Power Company, Jiangsu	江苏中电投常熟发电公司	3×300 1×330	1.2	N
71	Wangting Power Station, China Huadian Corporation	上海华电望亭发电厂	2×300 1×310 1×320	1.2	N
72	Pingxu Power Generation Co.Ltd, Huainan, Anhui	安徽淮南平圩发电有限公司	1×600 1×630	1.2	Y
73	Taiyuan No1 Phermal Power Station, Shanxi	山西太原第一热电厂	4×300 1×25	1.2	Y
74	Shidongkou Power Station, Shanghai	上海石洞口发电公司	3×300 1×320	1.2	Y
75	Jiangsu Huadian Qishuyan Electric Power Co.Ltd.	江苏华电戚墅堰发电有限公司	2×390 2×220	1.2	N
76	Jiangsu State power Jiangyin Sulong Electric Power Co.Ltd.	江苏国电江阴苏龙发电有限公司	2×137.5 2×140 2×330	1.2	Y
77	Jiangsu Tiansheng port Electric Power Plant	江苏天生港发电厂	4×137.5 2×330	1.2	Y
78	Henan Ping Dingshan Yaomeng Electric Power Co.Ltd.	河南平顶山姚孟发电有限责任公司	3×300 1×310	1.2	N
79	Tianjing Datang Panshan Electric Power Co.Ltd.	天津大唐盘山发电有限责任公司	2×600	1.2	
80	Hebei Datang Wantan Electric Power Co.Ltd.	河北大唐王滩发电有限公司	2×600	1.2	
81	Hebei Guohua Cangdong Electric Power Co.Ltd.	河北国华沧东发电有限责任公司	2×600	1.2	
82	Hebei Guohua Dingzhou Electric Power Co.Ltd.	河北国华定州发电有限公司	2×600	1.2	Y
83	Hebei Hengfeng Electric Power Co.Ltd. （含恒兴）	河北衡丰发电有限责任公司 （含恒兴）	4×300	1.2	Y
84	厂 Shanxi Datong NO.2 Power Plant	山西大同第二发电厂	6×200	1.2	N
85	Shanxi State Power Datong Electric Power Co.Ltd.	山西国电电力大同发电有限公司	2×600	1.2	

86	Shanxi Luneng Hequ Power Plant	山西鲁能河曲发电厂	2×600	1.2	Y
87	Shanxi Shentou NO.1 Power Plant	山西神头第一发电厂	6×200	1.2	
88	Shanxi Wangqu Power Plant	山西王曲电厂	2×600	1.2	N
89	Shanxi Wuxiang Hexin Power Plant	山西武乡和信电厂	2×600	1.2	N
90	Sunshine Power Station, shanxi	山西阳光发电厂	4×300	1.2	Y
91	Inner Mongolia Daihai Power Company	内蒙古岱海发电公司	2×600	1.2	
92	Inner Mongolia Huadian Hexi Power Company	内蒙古华电河西发电公司	2×600	1.2	Y
93	Inner Mongolia Fengzhen Power Plant	内蒙古丰镇发电厂	6×200	1.2	
94	Inner Mongolia Shangdu Electric Power Co.Ltd.	内蒙古上都发电有限责任公司	2×600	1.2	Y
95	Liaoning Jinzhou Donggang Electric Power Co.Ltd.	辽宁锦州东港电力有限公司	6×200	1.2	
96	Liaoning Qinghe Electric Power Co.Ltd.	辽宁清河发电有限责任公司	4×100 4×200	1.2	
97	Liaoning Tieling Power Plant	辽宁铁岭发电厂	4×300	1.2	N
98	Jilin Shuangliao Power Plant	吉林双辽发电厂	4×300	1.2	N
99	Heilongjiang Fulaerji General Plant	黑龙江富拉尔基总厂	6×200	1.2	
100	Shidongkou 2 Power Station, Shanghai	上海石洞口二厂	2×600	1.2	Y
101	Shanghai Waigaoqiao Electric Power Co.Ltd.	上海外高桥发电有限公司	4×300	1.2	Y
102	Shanghai Wujing NO.2 Electric Power Co.Ltd.	上海吴泾第二发电有限责任公司	2×600	1.2	Y
103	Jiangsu State Power Changzhou Power Plant	江苏国电常州电厂	2×600	1.2	N
104	Jiangsu Guohua (Taicang) Electric Power Co.Ltd.	江苏国华（太仓）发电有限公司	2×600	1.2	Y
105	Shazhou Power Station, Jiangsu	江苏沙洲电厂	2×600	1.2	Y
106	Jiangyin Ligang Electric Power Co.Ltd.	江阴利港发电股份公司	2×600	1.2	Y
107	Zhejiang Changxing Electric Power Co.Ltd.	浙江长兴发电有限公司	4×300	1.2	N

108	Zhejiang Beicang The First Electric Power Co.Ltd.	浙江北仑第一发电有限公司	2×600	1.2	Y
109	Anhui Maanshan The Secend Power Plant	安徽马鞍山第二发电厂	4×300	1.2	Y
110	Fujian Datang Ningde Power Plant	福建大唐宁德发电厂	2×600	1.2	Y
111	Fujian Songyu Power Plant	福建嵩屿电厂	4×300	1.2	Y
112	Fujian Kemen Power Plant	福建可门电厂	2×600	1.2	
113	Jiangxi Fengcheng Power Plant	江西丰城发电厂	4×300	1.2	N
114	Lae Power Station, Shandong	山东莱城电厂	4×300	1.2	N
115	Liaocheng Power Station, Shandong	山东聊城电厂	2×600	1.2	N
116	Henan Qinbei Power PLant	河南沁北电厂	2×600	1.2	N
117	Henan Huarun Shouyang Mountain Power Plant	河南华润首阳山电厂	2×600	1.2	N
118	Hubei Hanchuan Power Plant(汉新汉元）	湖北汉川发电厂（汉新汉元）	4×300	1.2	Y
119	Hubei Xiangfan Power Plant	湖北襄樊电厂	4×300	1.2	Y
120	Hubei Yangluo Power Plant	湖北阳逻电厂	4×300	1.2	Y
121	Hubei Yangluo Power Plant Phase III	湖北阳逻电厂三期	2×600	1.2	Y
122	Datang Jinzhu Mountain New Plant	大唐金竹山新厂	2×600	1.2	N
123	Datang Chaozhou International Electric Power Company	大唐国际潮州发电公司	2×600	1.2	N
124	Huaneng Shantou Power Station, Guangdong	广东华能汕头电厂	2×300 1×600	1.2	Y
125	shajiao A Power Station, Guangdong	广东沙角 A 电厂	2×300 3×200	1.2	Y
126	zhanjiang Power Station, Guangdong	广东湛江电厂	4×300	1.2	Y
127	Pearl River Power Station, Guangdong	广东珠江发电厂	4×300	1.2	Y
128	Anshun Power Station, Guizhou	贵州安顺发电厂	4×300	1.2	N
129	Guizhou Pannan Power Plant (Guangdong Electric Group)	贵州盘南发电厂（广东粤电集团）	2×600	1.2	N

130	Guizhou Qianxi Power Plant	贵州黔西发电厂	4×300	1.2	N
131	Guizhou Yaxi Power Plant	贵州鸭溪发电厂	4×300	1.2	N
132	Yunnan Qujing National Investment Electric Power Co.Ltd.	云南国投曲靖发电有限公司	4×300	1.2	N
133	Shanxi Baoji The Second Power Plant	陕西宝鸡第二电厂	4×300	1.2	N
134	Shanxi Hancheng The Second Electric Power Co.Ltd.	陕西韩城第二发电有限责任公司	2×600	1.2	
135	Shanxi Weihe Electric Power Co.Ltd.	陕西渭河发电有限公司	4×300	1.2	Y
136	Gansu Huaneng Pingliang Electric Power Co.Ltd.	甘肃华能平凉发电有限责任公司	4×300	1.2	N
137	Ningxia The Dam Electric Power Co.Ltd.	宁夏大坝发电有限责任公司	4×300	1.2	Y
138	Baosteel Power Station, Shanghai	上海宝钢电厂	3×350 1×149.7	1.2	N
139	Jiangsu Xinhai Power Plant	江苏新海发电厂	2×220 2×330 1×50 1×12 1×7.5 1×7 1×6	1.2	Y
140	Shanghai Huaneng Gas Turbine Electric Power Co.Ltd.	华能上海燃机发电有限责任公司	3×390	1.2	Y
141	Jiangsu Hangzhou Mid-level of the Mountain Electric Power Co.Ltd.	江苏杭州半山发电有限公司	3×390	1.2	Y
142	Heshan Power Station, Guangxi	广西合山发电厂	2×330 2×65 3×110	1.1	N
143	Anhui Datang Tianjiaan Electric Power Plant	安徽大唐田家庵发电厂	2×120 2×137.5 2×300	1.1	Y
144	Jiangsu Huadian Yangzhou Electric Power Plant	江苏华电扬州发电厂	2×220 2×330	1.1	Y
145	Shandong Century development of Electric Power Co.Ltd.	山东百年电力发展股份有限公司	4×220 2×110	1.1	
146	Huangpu Power Station, Guangdong	广东黄埔电厂	4×125 2×300	1.1	Y
147	Hebei Matou Electric Power General Plant	河北马头发电总厂	1×220 3×200 2×110 2×8	1.1	

148	Shanxi Taiyuan Second Thermal Power Plant	山西太原第二热电厂	3×200 3×50 1×300	1.1	Y
149	Shanxi Xindian Electric Power Plant	山西辛店电厂	2×225 2×300	1.1	Y
150	Shanxi Qinling (Qinhua)Electric Power Co.Ltd.	陕西秦岭（秦华）发电有限责任公司	4×200 2×125	1.1	
151	Shanxi Zhangze Electric Power Plant	山西漳泽发电厂	4×210 2×100	1.0	
152	Victory Power Station, shandong	山东胜利电厂	2×300 2×220	1.0	Y
153	Henan luoyang Shouyang Mountain Electric Power Plant	河南洛阳首阳山电厂	2×220 2×300	1.0	N
154	Shandong Huangtai Electric Power Plant	山东黄台电厂	1×25 2×35 1×60 1×100 1×110 2×330	1.0	Y
155	Heilongjiang Peony River The Second Electric Power Plant	黑龙江牡丹江第二发电厂	4×100 1×200 2×210	1.0	
156	Hunan Datang Liyang Electric Power Plant	湖南大唐耒阳电厂	2×210 2×300	1.0	N
157	Tianjing Guohua Panshan Electric Power Co.Ltd.	天津国华盘山发电有限责任公司	2×500	1.0	Y
158	山西大唐神二电厂	山西大唐神二电厂	2×500	1.0	N
159	Shanxi Shentou The Second Electric Power Plant	山西神头第二发电厂	2×500	1.0	N
160	Inner Mongolia Yimin Coal-fired electricity company	内蒙古伊敏煤电公司	2×500	1.0	N
161	Shandong Tengzhou New Resource Thermoelectric Company	山东滕州新源热电公司	2×150 2×350	1.0	N
162	Henan Zhenzhou Thermal Power Plant	河南郑州热电厂	5×200	1.0	
163	Shaoguan Power Station, Guangdong	广东韶关发电厂	2×200 2×300	1.0	Y
164	Guizhou Pan County Electric Power Plant (Qiangui Electric Power Plant)	贵州盘县发电厂（黔桂发电公司）	5×200	1.0	

Appendix 2 ASPEN Plus simulation modelling

Appendix 2.A Properties for the design coal and check coals (Zhouxian 2005)

Items	Symbols	Unit	Design coal	Check Coal
Coal type	Mixture of Yankuang and Jibei coal			
Moisture as received	Mar	%	8.00	10.00
Moisture air dried	Mad	%	2.48	2.51
Ash as received	Aar	%	24.40	27.75
Volatile matter, dry ash free	Vdaf	%	39	37.73
Lower heating value as received	Qnet.v.ar	kJ/kg	21271	19053
Lower heating value as received		kcal/kg	5080	4551
Hardgrove index	HGI		64	62
Wear coeficient	Ke		5.6	5.8
Carbon as received	Car	%	53.80	48.40
Hydrogen as received	Har	%	3.95	3.85
Oxygen as received	Oar	%	8.14	7.85
Nitrogen as received	Nar	%	1.11	1.25
Sulfur as received	Sar	%	0.60	0.90
Deformation temperature	$DT(T_1)$	^oC	1270	1200
Softening temperature	$ST(T_2)$	^oC	1350	1290
Flow temperature	$FT(T_3)$	^oC	1410	1350
Silicon oxide	SiO_2	%	58.61	56.03
Aluminium oxide	Al_2O_3	%	23.20	22.79
Ferric oxide	Fe_2O_3	%	6.50	6.67
Calcium oxide	CaO	%	2.90	6.48
Magnesium oxide	MgO	%	1.49	2.40

Potassium oxide	K_2O	%	2.02	1.79
Sodium oxide	Na_2O	%	0.71	0.89
Manganese oxide	MnO	%	0.14	0.19
Sulphur trioxide	SO_3	%	1.63	2.28
Others		%	2.8	0.48

Appendix 2B Simulation results from ASPEN for the coal combustion unit

Stream	AIR-IN	AIR0	G4	AIR	G5	FEEDCOAL	COAL-IN	AIRA	MC	G-C	AIRB	G
Actual stream	Air before going through fans	Air after going through fans	Air existing SCR	Preheated air going into boiler	Air from SCR after exchanged heat with cold air	Coal going into pulveriser	Coal passed pulveriser	Part of the preheated air used to heat up Coal-in	Mixed coal and preheated air	Decomposed coal	Air for combustion	Mixed gas after combustion
Temperature °C	25	30	373	342.9	114.8	25	25	342.9	43.6	25	342.9	1775.6
Pressure kPa	101.3	106.4	< 0.01	106.4	< 0.01	111.5	111.5	106.4	106.4	101.3	106.4	40.5
Mass Flow tonne/hr	3716.2	3716.2	4131.7	3716.2	4131.7	401.3	401.3	37	438.3	438.3	3679.2	4117.5
Mass Flow tonne/hr												
H_2O			348.8		348.8					45.9		342.1
N_2	2808.0	2808.0	2795.9	2808.0	2795.9			28.0	28.0	4.9	2780.1	2780.7
O_2	860.5	860.5	55.3	860.5	55.3			8.6	8.6	32.0	851.9	54.2
Ar	47.7	47.7	47.4	47.7	47.4			0.5	0.5		47.3	47.3
NO_2			<		< 0.001							0.003

			0.001									
NO			0.2		0.2							9.0
S			< 0.001		< 0.001					3.5		< 0.001
SO_2			7.1		7.1							7.1
SO_3			0.003		0.003							0.003
H_2										33.2		
Cl_2			trace		trace					0.4		trace
HCl			0.4		0.4							0.4
C										209.6		
CO_2			767.9		767.9							767.864
NH_3			0.009		0.009							
COAL						401.3	401.3		401.3			
ASH			108.9		108.9					108.9		108.9
Liq Frac 60F[42]												

[42] Liq Frac 60F: Mole volume percentage at 60F.

H_2O			0.051		0.051					0.046		0.051
N_2	0.781	0.781	0.787	0.781	0.787			0.781	0.781	0.009	0.781	0.785
O_2	0.21	0.21	0.014	0.21	0.014			0.21	0.21	0.054	0.21	0.013
Ar	0.009	0.009	0.009	0.009	0.009			0.009	0.009		0.009	0.009
NO_2			10 PPB		10 PPB							504 PPB
NO			48 PPM		48 PPM							0.002
S			trace		trace					0.002		trace
SO_2			868 PPM		868 PPM							871 PPM
SO_3			290 PPB		290 PPB							291 PPB
Cl_2			trace		trace					299 PPM		trace
HCl			87 PPM		87 PPM							88 PPM
CO_2			0.138		0.138							0.138
NH_3			4 PPM		4 PPM							

Appendix 2C Simulation results for flue gas for the power generation unit

Stream	G	G1	G2	G3
Actual Stream	Mixed gas after combustion	Mixed gas after exchange heat with super heater	Mixed gas after exchange heat with heater	Mixed gas going into SCR
Temperature ^oC	1775.6	763.4	481.1	350.8
Pressure kPa	40.53	10.13	1.01	0.01
Mass Flow tonne/hr	4117.5	4117.5	4117.5	4117.5
Mass Flow tonne/hr				
H_2O	342.1	342.1	342.1	342.1
N_2	2780.7	2780.7	2780.7	2780.7
O_2	54.2	54.2	54.2	54.2
Ar	47.3	47.3	47.3	47.3
NO_2	0.003	0.003	0.003	0.003
NO	9.0	9.0	9.0	9.0
S	< 0.001	< 0.001	< 0.001	< 0.001
SO_2	7.1	7.1	7.1	7.1
SO_3	0.003	0.003	0.003	0.003
Cl_2	trace	trace	trace	trace
HCl	0.4	0.4	0.4	0.4
CO_2	767.9	767.9	767.9	767.9
ASH	108.9	108.9	108.9	108.9
Liq Frac 60F				
H_2O	0.051	0.051	0.051	0.051
N_2	0.785	0.785	0.785	0.785
O_2	0.013	0.013	0.013	0.013

Ar	0.009	0.009	0.009	0.009
NO_2	504 PPB	504 PPB	504 PPB	504 PPB
NO	0.002	0.002	0.002	0.002
S	trace	trace	trace	trace
SO_2	871 PPM	871 PPM	871 PPM	871 PPM
SO_3	291 PPB	291 PPB	291 PPB	291 PPB
Cl_2	trace	trace	trace	trace
HCl	88 PPM	88 PPM	88 PPM	88 PPM
CO_2	0.138	0.138	0.138	0.138

Appendix 2D Simulation results for water and steam for the power generation unit

Stream	L-FEED	L-IN	L0	L1	L2	L3	L4	L5	L6	L7	L8
Actual Stream	Water goes into the high pressure pump	Water exits the pump	Water goes into the primary heater	Water exists the primary heater	Water exits the secondary pump	Water goes into the seconary heater	Water goesinto the economiser	Water exits the economiser	Steam passed the super heater	Steam passed the high pressur e turbine	Steam goes back to the heater
Temperature °C	99.2	110.7	166.9	185.9	219	294.4	298.5	338	600	344.7	330.3
Pressure kPa	101.33	3000	3000	3000	29820	29820	29820	28280	26110	4940	4940
Mass Flow tonne/hr	2347.1	2347.1	2347.1	2888.5	2888.5	2888.5	2888.5	2888.5	2888.5	2888.5	2347.1
Stream	L9	L10	L11	L12	L13	L14	L15	L16	L17	LC	LR
Actual Stream	Steam goes back to the steam system	Steam passed the heater	Steam exits the M turbine	Steam goes back to the low pressure heater	Steam goes back to the steam system	Water exits the low pressure turbine	Condensed water	Condensed water	Water after heatin g up L-IN	Part of the water after coming out from M-Turbine	Water after supplyin g heat to the capture unit
Temperature °C	330.3	600	315.9	313.2	313.2	48.2	70	263.1	162.3	313.2	162.3
Pressure kPa	4940	4470	654	654	654	11.3	101.33	4940	654	654	654
Mass Flow tonne/hr	541.4	2347.1	2347.1	1612.6	309.5	1612.6	1612.6	541.4	234.5	425	425

Appendix 2E Simulation results for DeNOx unit

Stream	NH3-IN	A-AIR	NH3	G3	G4
Actual Stream	NH3	Air of ammonia	Air with NH3	Mixed gas going into SCR	Mixed gas exits SCR
Temperature ^oC	25.0	25.0	24.8	350.8	373.0
Pressure kPa	101.3	101.3	101.3	0.0	< 0.01
Vapor Frac	1.0	1.0	1.0	1.0	1.0
Mass Flow tonne/hr	4.2	10.0	14.2	4117.5	4131.7
H_2O				342.1	348.8
N_2		7.6	7.6	2780.7	2795.9
O_2		2.3	2.3	54.2	55.3
Ar		0.1	0.1	47.3	47.4
NO_2				0.0	< 0.001
NO				9.0	0.2
S				< 0.001	< 0.001
SO_2				7.1	7.1
SO_3				0.0	0.0
Cl_2				trace	trace
HCl				0.4	0.4
CO_2				767.9	767.9
NH3	4.2		4.2		0.0
ASH				108.9	108.9
Liq Frac 60F					
H_2O				0.1	0.1
N_2		0.8	0.5	0.8	0.8
O_2		0.2	0.1	0.0	0.0
Ar		0.0	0.0	0.0	0.0

NO_2				504 PPB	10 PPB
NO				0.0	48 PPM
S				trace	trace
SO_2				871 PPM	868 PPM
SO_3				291 PPB	290 PPB
Cl_2				trace	trace
HCl				88 PPM	87 PPM
CO_2				0.1	0.1
NH_3	1.0		0.4		4 PPM

Appendix 2F Simulation result for ESP

Stream	G6	ASH	G7
Actual stream	Gas going into ESP	Ash coming out from ESP	Gas exits ESP
Temperature C	114.8	114.8	114.8
Pressure kPa	101.3	88.0	88.0
Mass VFrac	1.0	0.0	1.0
Mass Flow tonne/hr	4131.7	105.3	4026.4
Mass Flow tonne/hr			
H_2O	348.8		348.8
N_2	2795.9		2795.9
O_2	55.3		55.3
AR	47.4		47.4
NO_2	< 0.001		< 0.001
NO	0.2		0.2
S	trace		trace
SO_2	7.1		7.1
SO_3	0.0		0.0
CL_2	trace		trace
HCL	0.4		0.4
CO_2	767.9		767.9
NH_3	0.0		0.0
ASH	108.9	105.3	3.6

Appendix 2G Gypsum production rate from FGD（2×1000MW）

Unit capacity		Gypsumproduction rate t/h	Gypsum production ratet/d	Gypsum production rate10^4t/a
Design coal	1×1000MW	13.95	279	7.6725
	2×1000MW	27.9	558	15.345
Check coal	1×1000MW	17.53	350.6	9.6415
	2×1000MW	35.06	701.2	19.283

Note: The plant is estimated to run up to 20 hours per day and 5500 hours per year.

Appendix 2H Parameter for the FGD

No	Items		Unit	Design coal	Check coal	Notes
1	FGD flue gas rate		Nm^3/h.unit	4810000	4830000	Dry flue gas
2	FGD efficiency		%	>95		
3	FGD inlet temperature		^oC	115		
4	Stack inlet temperature		^oC	≥80		
5	Stack outlet SO_2 concentration		mg/Nm^3	49.28	61.69	
6	Stack outlet ash concentration at		mg/Nm^3	≤50		
7	SO_2 reduction rate		t/h.unit	4.2028	5.2839	
8	Liquid/flue gas ratio		L/Nm^3	～13		
9	Calcium/sulphur ratio			1.03		
10	Sorbent	Limestone size		325μm， passing rate 90%		44μm
		Purity of limestone	%	≥90		
		Consumption rate of limestone	t/h	15.04	18.9	
	Gypsum ($CaSO_4.2H_2O$) production rate		t/h	27.9	35.06	

11	Purity	%	90	
	Water	%wt	≤10	
12	Water consumption	t/h	240	

Appendix 2I Pollutant emission estimates for the Zhouxian plant

Items			Unit	Design coal	Check coal
Stack		Stack type		One double tube stack	
		Height	m	240	
		Outlet diameter	m	10	
Pollutants	SO_2	Actual emission rate	t/h	0.884	1.112
		Allowed emission rate	t/a	56872	
		Actual emission concentration	mg/m^3	98.56	123.38
		Allowed emission concentration	mg/m^3	2100	
	Ash	Actual emission concentration	mg/m^3	35.05	42.62
		Allowed emission concentration	mg/m^3	500	
		Actual emission rate	t/h	0.314	0.384
	NO_X	Actual emission concentration	Nox＜450mg/m^3 with low Nox burner		
		Allowed emission concentration	＜650mg/m^3		
Note: ① SCR efficiency is 99.65%， DeSOx efficiency is 90% ② Excess air ratio is 1.4 based on the dry flue gas. ③ Plant running at 5500 hours/year.					

Appendix 2J FGD simulation results

Stream	G7	A-H	CACO3	AIR-FGD	CASO4	SS	LL	G8
Actual Stream	Gas going into FGD	Water for FGD	CACO3 for FGD	Air for FGD	Recated CASO4	Solid Sulphur	Liquid going back to FGD	Gas exits FGD
Temperature °C	114.8	25.0	25.0	25.0	50.0	50.0	50.0	50.0
Pressure kPa	88.0	101.3	101.3	101.3	91.2	91.2	91.2	91.2
Mass Flow total tonne/hr	4026.4	8.7	10.5	0.8	174.7	33.4	141.3	4013.0
Mass Flow Total tonne/hr								
H_2O	348.8	8.7			157.0	15.7	141.3	341.9
N_2	2795.9			0.6	0.0	0.0		2796.5
O_2	55.3			0.2	< 0.001	< 0.001		53.9
AR	47.4			0.0	< 0.001	< 0.001		47.4
NO_2	< 0.001				trace	trace		< 0.001
NO	0.2				trace	trace		0.2
S	trace							
SO_2	7.1				< 0.001	< 0.001		0.6
SO_3	0.0				0.0	0.0		0.1
CL_2	trace				trace	trace		trace
HCL	0.4				trace	trace		trace
CO_2	767.9				0.0	trace		772.5
HCO_3-					0.0	0.0		
CO_3--					trace	0.0		
OH-		trace			0.0	< 0.001	trace	
CA++					0.3	0.3		
$CACO_3$(S)			10.5					

HSO_3-					trace	trace		
SO_3-					trace	trace		
NH_3	0.0				trace	trace		< 0.001
CL-					0.4	0.4		
SO_4--					0.2	0.2		
$SALT_2$					13.3	13.3		
NH_4+					0.0	0.0		
ASH	3.6				3.6	3.6		
Liq Frac 60F								
H_2O	0.1	1.0			1.0	1.0	1.0	0.1
N_2	0.8			0.8	17 PPM	171 PPM		0.8
O_2	0.0			0.2	533 PPB	5 PPM		0.0
AR	0.0			0.0	405 PPB	4 PPM		0.0
NO_2	10 PPB				6 PPB	64 PPB		10 PPB
NO	48 PPM				25 PPB	248 PPB		48 PPM
S	trace							
SO_2	868 PPM				2 PPM	22 PPM		78 PPM
SO_3	290 PPB				13 PPM	127 PPM		7 PPM
CL_2	trace				trace	trace		trace
HCL	87 PPM				trace	trace		trace
CO_2	0.1				115 PPM	357 PPB		0.1
NH_3	4 PPM				20 PPB	200 PPB		74 PPB

Appendix 2K Simulation result for the capture unit

	LIQ-IN	LIQ	G9	GAS-IN	GAS-OUT	F-GAS	LIQ-OUT	RICH-IN	CO_2	LEAN
Actual Stream	Liquid going into the pump for absorber	Pressurised liquid for absorber	Gas coming from FGD	Gas going into absorber	Gas coming out from absorber	Gas without CO2	Liquid with CO2	Liquid going into desorber	CO2 from desorber	Lean solvent from desorber
Temperature ^oC	30.0	30.0	50.0	50.0	54.8	52.1	54.6	102.0	72.6	103.9
Pressure kPa	101.3	102.3	91.2	102.3	101.3	101.3	101.3	101.3	101.3	101.3
Vapor Frac	0.0	0.0	1.0	1.0	1.0	1.0	0.0	< 0.001	1.0	0.0
Mass Flow tonne/hr	7605.1	7605.1	4013.0	4013.0	3267.2	3274.5	8350.9	8350.9	793.3	7557.5
H_2O	5320.0	5320.0	341.9	341.9	293.5	297.2	5359.3	5359.3	94.6	5273.7
N_2	0.0	0.0	2796.5	2796.5	2796.5	2796.5	0.0	0.0	0.0	trace
O_2	0.0	0.0	53.9	53.9	53.8	53.8	0.1	0.1	0.1	trace
AR	0.0	0.0	47.4	47.4	47.3	47.3	0.1	0.1	0.1	trace
NO_2	trace	trace	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	trace	trace
NO	trace	trace	0.2	0.2	0.2	0.2	< 0.001	< 0.001	< 0.001	trace
SO_2	0.0	0.0	0.6	0.6	0.6	0.6	0.1	0.1	0.0	0.0
SO_3	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0

CL_2	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace
HCL	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace
CO_2	3.5	3.5	772.5	772.5	74.8	79.0	0.5	0.5	697.9	< 0.001
HCO_3-	0.3	0.3		< 0.001			30.6	30.6		0.1
CO_3--	trace	trace		trace			0.8	0.8		0.0
H_3O+	0.0	0.0		< 0.001			trace	trace		trace
OH-	trace	trace		trace			0.0	0.0		0.1
NH_3	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	trace	< 0.001
MEA	2280.0	2280.0			0.6	0.0	364.6	364.6	0.4	2269.3
MEAH+	0.5	0.5					989.9	989.9		5.6
MEACOO-	0.6	0.6					1604.9	1604.9		8.6
Liq Frac 60F										
H_2O	0.7	0.7	0.1	0.1	0.1	0.1	0.9	0.9	0.1	0.7
N_2	256 PPB	256 PPB	0.8	0.8	0.9	0.9	9 PPM	9 PPM	55 PPM	trace
O_2	1 PPM	1 PPM	0.0	0.0	0.0	0.0	40 PPM	40 PPM	242 PPM	trace
AR	868 PPB	868 PPB	0.0	0.0	0.0	0.0	30 PPM	30 PPM	182 PPM	trace
NO_2	1 PPB	1 PPB	10 PPB	10 PPB	10 PPB	11 PPB	3 PPB	3 PPB	7 PPB	1 PPB

NO	trace	trace	48 PPM	48 PPM	55 PPM	55 PPM	10 PPB	10 PPB	63 PPB	trace
SO_2	4 PPM	4 PPM	78 PPM	78 PPM	84 PPM	86 PPM	12 PPM	12 PPM	39 PPM	4 PPM
SO_3	4 PPM	4 PPM	7 PPM	7 PPM	7 PPM	8 PPM	6 PPM	6 PPM	5 PPM	4 PPM
CL_2	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace
HCL	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace
CO_2	566 PPM	566 PPM	0.1	0.1	0.0	0.0	98 PPM	98 PPM	0.9	21 PPB
NH_3	9 PPB	9 PPB	74 PPB	74 PPB	81 PPB	84 PPB	16 PPB	16 PPB	30 PPB	8 PPB
MEA	0.3	0.3			102 PPM	700 PPB	0.1	0.1	442 PPM	0.3

Simulation result for the capture unit (cont)

	REUSE	RL	RM	A-M	A-W	M-LIQ
Actual stream	LEAN after passed heat exchanger	Recycled liquid	Recycled MEA	Added MEA	Added water	MEA solvent
Temperature ^{O}C	57.9	57.9	52.2	25.0		57.8
Pressure kPa	101.3	121.6	101.3	101.3	101.3	101.3
Vapor Frac	0.0	0.0	0.0	0.0		0.0
Mass Flow tonne/hr	7557.5	7557.5	89.7	0.0	0.0	7647.3
Mass Flow tonne/hr						
H_2O	5273.7	5273.8	88.4			5362.2
N_2	trace		0.0			0.0
O_2	trace		0.0			0.0
AR	trace	trace	0.0			0.0
NO_2	trace	trace	trace			trace
NO	trace		trace			trace
SO_2	0.0	0.0	0.0			0.0
SO_3	0.0	0.0	0.0			0.0
CL_2	trace	trace	trace			trace
HCL	trace	trace	trace			trace
CO_2	< 0.001	3.3	0.0			3.5
HCO_3-	0.1	0.3	0.1			0.3
CO_3--	0.0	trace	0.0			trace
H_3O+	trace	0.0	trace			0.0
OH-	0.1	trace	< 0.001			trace
NH_3	< 0.001	< 0.001	trace			< 0.001
MEA	2269.3	2279.0	0.5	0.0		2280.0
MEAH+	5.6	0.6	0.4			0.6

Liq Frac 60F						
H_2O	0.7	0.7	1.0			0.7
N_2	trace		22 PPM			254 PPB
O_2	trace		98 PPM			1 PPM
AR	trace	trace	74 PPM			863 PPB
NO_2	1 PPB	1 PPB	7 PPB			1 PPB
NO	trace		28 PPB			trace
SO_2	4 PPM	4 PPM	28 PPM			4 PPM
SO_3	4 PPM	4 PPM	14 PPM			4 PPM
CL_2	trace	trace	trace			trace
HCL	trace	trace	trace			trace
CO_2	21 PPB	533 PPM	14 PPM			565 PPM
NH_3	8 PPB	8 PPB	73 PPB			9 PPB
MEA	0.3	0.3	0.0	1.0		0.3

Appendix 2L Simulation result for compression unit

	C1	C2	C3	C4	C5
Temperature ^oC	610.4	50.0	50.0	50.0	30.0
Pressure kPa	11000.0	11000.0	11000.0	11000.0	11000.0
Vapor Frac	1.0	0.8	1.0	0.0	0.0
Mass Flow tonne/hr	793.3	793.3	696.3	97.0	696.3
H_2O	94.6	94.6	2.5	92.1	2.5
N_2	0.0	0.0	0.0	< 0.001	0.0
O_2	0.1	0.1	0.1	0.0	0.1
AR	0.1	0.1	0.1	0.0	0.1
NO_2	trace	trace	trace	trace	trace
NO	< 0.001	< 0.001	< 0.001	trace	< 0.001
SO_2	0.0	0.0	0.0	0.0	0.0
SO_3	0.0	0.0	0.0	0.0	0.0

CL_2	trace	trace	trace	trace	trace
HCL	trace	trace	trace	trace	trace
CO_2	697.9	697.9	693.5	4.4	693.5
HCO_3-		0.0		0.0	
CO_3--		trace		trace	
H_3O+		0.0		0.0	
OH-		trace		trace	
NH_3	trace	trace	trace	trace	trace
MEA	0.4	0.4	0.0	0.4	0.0
Liq Frac 60F					
H_2O	0.1	0.1	0.0	0.9	0.0
N_2	55 PPM	55 PPM	62 PPM	316 PPB	62 PPM
O_2	242 PPM	242 PPM	241 PPM	250 PPM	241 PPM
AR	182 PPM	182 PPM	180 PPM	201 PPM	180 PPM
NO_2	7 PPB	7 PPB	3 PPB	49 PPB	3 PPB
NO	63 PPB	63 PPB	69 PPB	6 PPB	69 PPB
SO_2	39 PPM	39 PPM	25 PPM	167 PPM	25 PPM
SO_3	5 PPM	5 PPM	2 PPM	38 PPM	2 PPM
CL_2	trace	trace	trace	trace	trace
HCL	trace	trace	trace	trace	trace
CO_2	0.899	0.899	0.997	0.1	0.997
NH_3	30 PPB	30 PPB	6 PPB	239 PPB	6 PPB
MEA	442 PPM	436 PPM	1 PPM	0.0	1 PPM

Appendix 3 Online Survey Questionnaire (translated from Chinese version)

Stakeholder Consultation Questionnaire on CO_2 Capture Ready at New-build Coal-fired Power Plants in China for CAPPCCO Project

Welcome to the CCS survey. This questionnaire is part of the CAPPCCO (UK-China Chinese Advanced Power Plant Carbon Capture Options) Project. The aim of the project is to understand the engineering and economic feasibility of making new plants to achieve CO_2 Capture Ready status (or 'CCS Ready').

At the request of the Gleneagles G8 summit, the IEA Greenhouse Gas Programme published a study which identified the following key elements for CCR power plants:

- A CO_2 capture ready power plant is a plant which can include CO_2 capture when the necessary regulatory or economic drivers are in place. The aim of building plants that are capturing ready is to reduce the risk of stranded assets and carbon lock-in.
- Developers of capture ready plants should take responsibility for ensuring that all known factors in their control that would prevent installation and operation of CO_2 capture have been identified and eliminated. This might include:
  - A study of options for CO_2 captures retrofit and potential pre-investments
  - Inclusion of sufficient space and access for the additional facilities
  - Identification of reasonable routes to storage of CO_2
- Competent authorities involved in permitting power plants should be provided with sufficient information to be able to judge whether the developer has met these criteria.

For more technical info on CO_2 capture ready, please visit information briefing website:

http://www.captureready.com/EN/Channels/Research/showDetail.asp?objID=8&isNew=

For more information about CAPPCCO, please visit project briefing website:

http://www.captureready.com/EN/Channels/Projects/showDetail.asp?objID=125&ClassID=5

We estimate it should take you approximately 15 to 20 minutes to fill out the questionnaire. Please mark the statement that comes **closest to your opinion**. All answers will be treated anonymously and in strict confidence.

Finally, we appreciate your participation.

Page 1 --

Demographic Information

Q1. CCS is a relative new idea in China, have you heard of CO_2 Capture and Storage (CCS) and CO_2 Capture Ready (CCR) before this survey?

- ❑ Yes, I have heard of both CCS and CCS
- ❑ I only know of CCS
- ❑ I only know of CCR
- ❑ No, I am not familiar with either term

Q2. On average, how much of your working time is spent directly on **energy** issues?

- ❑ >90%
- ❑ 70 - 90%
- ❑ 50 – 70%
- ❑ 30 – 50%
- ❑ 10% - 30%
- ❑ 0% - 10%
- ❑ 0%

Q3. On average, how much of your working time is spent directly on **climate change** issues?

- ❑ >90%
- ❑ 70 - 90%
- ❑ 50 – 70%
- ❑ 30 – 50%
- ❑ 10% - 30%
- ❑ 0% - 10%
- ❑ 0%

Q4. On average, how much of your working time is spent directly on **CO_2 Capture and Storage (CCS)** issues?

- ❑ >90%
- ❑ 70 - 90%
- ❑ 50 – 70%
- ❑ 30 – 50%
- ❑ 10% - 30%
- ❑ 0% - 10%
- ❑ 0%

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Q5. Where is your institution?

- ❑ Beijing
- ❑ Tianjin
- ❑ Shanghai
- ❑ Guangdong
- ❑ Heilongjiang,
- ❑ Jilin
- ❑ Liaoning
- ❑ Ningxia
- ❑ Gansu
- ❑ Inner Mongolia
- ❑ Shandong
- ❑ Hebei
- ❑ Shanxi
- ❑ Zhejiang
- ❑ Jiangsu
- ❑ Anhui
- ❑ Hubei
- ❑ Henan

- ❑ Shaanxi
- ❑ Sichuan
- ❑ Chongqing
- ❑ Guizhou
- ❑ Fujian
- ❑ Jiangxi
- ❑ Hunan
- ❑ Yunnan
- ❑ Guangxi
- ❑ Hainan
- ❑ Xinjiang
- ❑ Tibet
- ❑ Qinghai
- ❑ Hongkong
- ❑ Macao
- ❑ Taiwan

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Q6. What's the type of your institution?

- ❑ National Government Departments
- ❑ Provincial & County Government Departments
- ❑ Power Generation Industry (go to I7)
- ❑ Engineering Design Institute (go to I7)
- ❑ Chemical Industry (go to I7)
- ❑ Thermal Engineering Academia (go to I7)
- ❑ None of above

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Government officer's questions

G7. How difficult do you think it will be to significantly reduce global CO_2 emissions in the next two decades?

- ❑ Very difficult
- ❑ Difficult
- ❑ Moderate
- ❑ Easy
- ❑ Very easy
- ❑ Unsure

G8. How important is climate change to your organization?

- ❑ Very important
- ❑ Important
- ❑ Moderately important
- ❑ Less important
- ❑ Not important
- ❑ Unsure

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Government officer's questions

---- Knowledge & Perceptions of CO_2 Capture and Storage

G9. Could you describe the necessity of CCS in achieving deep GHG emissions reductions?

- ❑ Very necessary
- ❑ Probably necessary
- ❑ Necessary only if alternatives cannot achieve
- ❑ Probably unnecessary
- ❑ Not necessary at all
- ❑ Unsure

G10. Which of the following capture technologies would be possible in China for the first 10 plants? *you may choose more than one

- ❑ Post-combustion Capture (normally in pulverized-coal power plants)
- ❑ Pre-combustion Capture in IGCC plants
- ❑ CCS at poly-generation, coal to liquid, refinery plants
- ❑ Oxyfuel (a novel process at pulverized-coal power plants)
- ❑ Unsure

G10a. Which of the following capture technologies would be possible in China for the first 100 plants? *you may choose more than one

- ❑ Post-combustion Capture (normally in pulverized-coal power plants)
- ❑ Pre-combustion Capture in IGCC plants
- ❑ CCS at poly-generation, coal to liquid, refinery plants
- ❑ Oxyfuel (a novel process at pulverized-coal power plants)
- ❑ Unsure

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Government officer's questions

G11. Which of the following carbon storage technologies would be possible in China for the first 10 storage sites? *you may choose more than one

- ❑ Enhanced Oil Recovery
- ❑ Depleted Oil or Gas Reservoir
- ❑ Geological Storage in Saline Aquifer
- ❑ Enhanced Coal Bed Methane Recovery (Store at coal seam)
- ❑ Others, please indicate_____________________
- ❑ Unsure

G11a. Which of the following carbon storage technologies would be possible in China for the first 100 storage sites? *you may choose more than one

- ❑ Enhanced Oil Recovery
- ❑ Depleted Oil or Gas Reservoir
- ❑ Geological Storage in Saline Aquifer
- ❑ Enhanced Coal Bed Methane Recovery (Store at coal seam)
- ❑ Others, please indicate_____________________
- ❑ Unsure

G12.What is your general perspectives on designing a plant to be CO_2 capture ready?

- ❑ Strong support
- ❑ Support
- ❑ Fair
- ❑ Oppose
- ❑ Strong oppose
- ❑ No comment
- ❑ Not sure

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Government officer's questions

---- **Policies**

G13. Which of the following potential policies you would consider most effective to enable CO_2 capture ready (CCR) investment in China within this decade (2010-2020)?

- ❑ Policy mandate for new plants to retrofit capture by a certain date
- ❑ Provide direct financial subsidy on CCR investment
- ❑ Support from foreign public institutions in CCR
- ❑ Market-based incentives
- ❑ Not sure

G14. Which government departments would you consider might help to achieve their demand on making new coal-fired power plants CO_2 capture ready is complied in China? *You may choose more than one institution

- ❑ State Council
- ❑ National Development and Reform Commission
- ❑ Ministry of Environmental Protection
- ❑ State Electricity Regulatory Commission
- ❑ Ministry of Finance
- ❑ Ministry of Science and Technology
- ❑ Provincial governments
- ❑ Other local governments
- ❑ Other ____________________________
- ❑ Unsure

G15. Which government departments would you consider would find a CO_2 capture ready at new coal-fired power plants conflict with their objective in China? *You may choose more than one institution

- ❑ State Council
- ❑ National Development and Reform Commission
- ❑ Ministry of Environmental Protection
- ❑ State Electricity Regulatory Commission
- ❑ Ministry of Finance
- ❑ Ministry of Science and Technology
- ❑ Provincial governments
- ❑ Other local governments
- ❑ Other ____________________________
- ❑ Unsure

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Government officer's questions

G17. Do you agree with the following statement with respect to the effect of making new plants CO_2 Capture Ready in China? (1 is strongly agree, 3 is neutral and 5 is strongly disagree)

	1	2	3	4	5
★ Benefit Chinese CCS equipment manufacturers	❑	❑	❑	❑	❑
★ Benefit Chinese energy firms investing in CCS technologies	❑	❑	❑	❑	❑
★ Add credit to Chinese government in the climate area	❑	❑	❑	❑	❑
★ Attract foreign investment	❑	❑	❑	❑	❑

G18. Are you likely to accept building new advanced coal-fired power plants with CO_2 Capture Ready features which ease retrofitting to CO_2 Capture in their lifetime if it **incurs 3% extra fixed capital expenditure**?

- ❑ Yes, I will accept (go to G21)
- ❑ No, it is not acceptable at any cost (go to G21)
- ❑ No, but I may accept if the cost is lower(go to G19)
- ❑ Unsure

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Government officer's questions

G19. Are you likely to accept building new advanced coal-fired power plants with CO_2 Capture Ready features which ease retrofitting to CO_2 Capture in their lifetime if it **incurs 1% extra fixed capital expenditure**?

- ❑ Yes, I will accept (go to G21)
- ❑ No, it is not acceptable at any cost (go to G21)
- ❑ No, but I may accept if the cost is lower(go to G20)
- ❑ Unsure

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Government officer's questions

G20. Are you likely to accept building new advanced coal-fired power plants with CO_2 Capture Ready features which ease retrofitting to CO_2 Capture in their lifetime if it **incurs 0.5% extra fixed capital expenditure**?

- ❑ Yes, I will accept (go to G21)
- ❑ No, it is not acceptable at any cost (go to G21)
- ❑ No, but I may accept if the cost is lower(go to G20)
- ❑ Unsure

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Government officer's questions

G21.Assume retrofitting to full scale CO_2 capture could create 100 job opportunities and 25% higher revenue at a 600MW coal-fired power plant. Are you likely to support building new advanced coal-fired power plants with CO_2 Capture Ready features which ease retrofitting to CO_2 Capture in their lifetime if it **reduces power generation efficiency by 0.5%** and require 1% higher levelised cost of electricity?

- ❑ Yes, I will support anyway. (go to G22)
- ❑ Yes, I will support because the social and economic benefits (go to G22)
- ❑ No, it is not acceptable (end)
- ❑ Unsure

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Government officer's questions

G22.Do you think governments may provide the following support to new plants to be CO_2 capture ready (CCR) (1 is strongly agree, 3 is neutral and 5 is strongly disagree)

	1	2	3	4	5
★ Incentivize land reservation on-site for capture unit	❑	❑	❑	❑	❑
★ Support modifying plant design to east future retrofitting	❑	❑	❑	❑	❑
★ Consider access to CO_2 storage site in authorization	❑	❑	❑	❑	❑
★ Government would facilitate the development of CO_2 transport and storage infrastructure	❑	❑	❑	❑	❑

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Industrial stakeholder's questions

I7. What is your expert area? *you may choose more than one

- ❑ Power engineering
- ❑ Chemical engineering
- ❑ Civil engineering
- ❑ Environment science
- ❑ Management & Finance
- ❑ Other, please specify ___________

I8. How important is climate change to your organization?

- ❑ Very important
- ❑ Important
- ❑ Moderately important
- ❑ Less important
- ❑ Not important
- ❑ Unsure

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Industrial questions

I9. How difficult do you think it will be to significantly reduce global CO_2 emissions in the next two decades?

- ❑ Very difficult
- ❑ Difficult
- ❑ Moderate
- ❑ Easy
- ❑ Very easy
- ❑ Unsure

I10. Which of the following carbon storage technologies sound promising in China? *you may choose more than one

- ❑ Enhanced Oil Recovery
- ❑ Depleted Oil or Gas Reservoir
- ❑ Geological Storage in Saline Aquifer
- ❑ Enhanced Coal Bed Methane Recovery (Store at coal seam)
- ❑ Others, please indicate_____________________
- ❑ Unsure

I11.What is your general perspective on CO_2 capture ready investment?

- ❑ Strong support
- ❑ Support
- ❑ Fair
- ❑ Oppose
- ❑ Strong oppose
- ❑ Not sure

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Industrial questions

I12. Which of the following potential factors are likely to influence CO_2 capture ready (CCR) decisions in China within the next 10 years (2010-2020)? *you may choose more than one

- ❑ Access to storage site
- ❑ Sufficient space on-site
- ❑ Water supply
- ❑ Management's interests
- ❑ Knowledge of chemical processing
- ❑ Availability of coal supply
- ❑ Other factors, please specify _______________________
- ❑ Not sure

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Industrial questions (extending question I12)

For Industry selecting “spaces on site”

I12a What should be a reasonable amount of extra space to host the capture unit, with 2*600MW PC as baseline?

- ❑ Same size as the power plant
- ❑ Half the size of the power plant
- ❑ 1/4 the size of the power plant
- ❑ 1/8 the size of the power plant
- ❑ Doesn’t matter with size, but the actual location of the capture unit will not fit anywhere
- ❑ Not sure

For Industry selecting “water supply”

I12b What should be the acceptable extra water consumption of the capture unit, with 2*600MW as baseline?

- ❑ Same amount of the original power plant
- ❑ Half the amount of the power plant
- ❑ 1/4 the amount of the power plant
- ❑ 1/8 the amount of the power plant
- ❑ No extra water should be consumed for CCS
- ❑ Not sure

For Industry selecting “management’s decision”

I12c Why do you think a plant owner will be interested/ not interested in making new power plant capture ready?

- ❑ Perceptions of accepting advance technology
- ❑ Perceptions of climate change problem
- ❑ Institutional regulation or convention
- ❑ Lack of government endorsement
- ❑ Other, please specify ___________________
- ❑ Not sure

For Industry selecting “knowledge of chemical processing”

I12d How would you like to solve the gap of knowledge between thermal engineering and chemical engineering at a capture ready plant?

- ❑ Outsourcing the unit to a chemical company
- ❑ Hiring people from chemical industry
- ❑ Training staffs onsite to operate the plant
- ❑ It is mainly an operational job, no need to worry
- ❑ Impossible to solve the problem
- ❑ Not sure

For Industry selecting “coal supply”

I12e Why do you think coal supply is the biggest impact?

- ❑ It can help power company to store more coal
- ❑ There is not enough room for the extra coal
- ❑ It is impossible to get the extra coal
- ❑ It is possible but too expensive to get the extra coal
- ❑ Impossible to solve the problem
- ❑ Not sure

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Industrial questions

I13. Which factor would you perceive as potential significant barriers to prevent power plant from capture retrofit? *you may select more than one

- ❑ Electricity loss after retrofitting
- ❑ Running the power plant at full load most of the time after retrofitting
- ❑ Efficiency loss of plant
- ❑ Handing capture unit on-site
- ❑ Storing carbon dioxide on-site
- ❑ Coal supply
- ❑ No factor
- ❑ Other, please specify ___________________
- ❑ Unsure

I14. Which institutions would you consider as the most appropriate to suggest suitable locations at which to build CO_2 capture ready coal-fired power plants in China? *You may choose more than one institution

- ❑ Plant Investors
- ❑ Electricity Planning institution
- ❑ Chemical Process Design institution
- ❑ Power companies
- ❑ Power Grids
- ❑ Oil/Gas companies
- ❑ State Electricity Regulatory Commission
- ❑ National government
- ❑ Local government
- ❑ Other ___________________________
- ❑ Unsure

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Industrial questions

I17. Do you agree with the following statement with respect to the effect of making new plants CO_2 Capture Ready in China? (1 is strongly agree, 3 is neutral and 5 is strongly disagree)

	1	2	3	4	5
★ Benefit Chinese CCS equipment manufacturers	❑	❑	❑	❑	❑
★ Benefit Chinese energy firms invest in CCS technologies	❑	❑	❑	❑	❑
★ Add credit to Chinese government in climate area	❑	❑	❑	❑	❑
★ Attract foreign investment	❑	❑	❑	❑	❑

I18. Ae you likely to accept building new advanced coal-fired power plants with CO_2 Capture Ready features which ease retrofitting to CO_2 Capture in their lifetime if it **incurs 3% extra fixed capital expenditure**?

- ❑ Yes, I will accept (go to I21)
- ❑ No, it is not acceptable at any cost (go to I21)
- ❑ No, but I may accept if the cost is lower(go to I19)
- ❑ Unsure

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Industrial questions

I19. Are you likely to accept building new advanced coal-fired power plants with CO_2 Capture Ready features which ease retrofitting to CO_2 Capture in their lifetime if it **incurs 1% extra fixed capital expenditure**?

- ❑ Yes, I will accept (go to I21)
- ❑ No, it is not acceptable at any cost (go to I21)
- ❑ No, but I may accept if the cost is lower(go to I20)
- ❑ Unsure

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Industrial questions

I20. Are you likely to accept building new advanced coal-fired power plants with CO_2 Capture Ready features which ease retrofitting to CO_2 Capture in their lifetime if it **incurs 0.5% extra fixed capital expenditure**?

- ❑ Yes, I will accept
- ❑ No, it is not acceptable at any cost
- ❑ No, but I may accept if the cost is lower
- ❑ Unsure