ADB TA-7286 (PRC) People's Republic of China
Carbon Dioxide Capture and Storage Demonstration
– Strategic Analysis and Capacity Strengthening

Roadmap for the Demonstration of Carbon Capture and Storage (CCS) in China

Final Report

June 2011

ADB TA-7286 (PRC) People's Republic of China

Carbon Dioxide Capture and Storage Demonstration
– Strategic Analysis and Capacity Strengthening

Roadmap for the Demonstration of Carbon Capture and Storage (CCS) in China

Final Report

June 2011

Report submitted by Project Team

Prof. J. YAN – Team Leader & CCS Experts
Prof. H. JIN – National Co-leader
Prof. Li Z., Dr. J. Hetland, Dr. Teng F., Prof. Jiang K.J., Ms. C. J. Vincent, Dr. A. Minchener, Prof. Zeng RS, Prof. Shen PP, Dr. X. D. Pei, Dr. Wang C., Prof. Hu J, Dr. Zhang JT

TABLE OF CONTENTS

TABLES

FIGURES

ABBREVIATIONS AND ACRONYMS

ACCA21	Administrative Centre for China's Agenda 21
ADB	Asian Development Bank
AEA	Atomic Energy Authority
AF	Adaptation Fund
AHP	Analytic Hierarchy Process
API	American Petroleum Institute
ASU	Air separation unit
BERR	Business, Enterprise & Regulatory Reform
BGS	British Geological Survey
CACHET	Carbon Dioxide Capture and Hydrogen Production from Gaseous Fuels
CAGS	Chinese Academy of Geological Sciences
CAPPCCO	Chinese Advanced Power Plant Carbon Capture Options
CAS	Chinese Academy of Sciences
CBM	Coal Bed Methane
CCCDP	China-Canada CO2-ECBM R&D Project
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CEFPF	Clean Energy Financing Partnership Facility
CHNG	China Huaneng Group
CHP	Combined heat&power
CIF	Climate Investment Funds
COACH	Cooperation Action within CCS China-EU
COE	Cost of Electricity
CPF	Carbon Partnership Facility
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSLF	Carbon Sequestration Leadership Forum
CTF	The World Banks Clean Technology Fund
CTL	Coal to liquid
CUCBM	China United Coal Bed Methane Corporation
DECC	Department of Energy and Climate Change, UK
DME	Dimethyl ether
DS	Development Solutions Europe Ltd.
EC	European Commission
ECBM	Enhance coal bed methane
EA	Executive Agency
ACCA21	Administrative Centre for China's Agenda 21
ADB	Asian Development Bank
AEA	Atomic Energy Authority
AF	Adaptation Fund
AHP	Analytic Hierarchy Process
EGR	Enhance Gas Recovery
EIA	Energy Information Administration
ELC	Enhanced Low Carbon

EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
ETS	Emissions Trading Scheme
EU	European Union
FCPF	Forest and Carbon Partnership Fund
FYP	Five-Year Plan
GCCSI	Global Carbon Capture and Storage Institute
GEF	Global Environmental Facility
GHG	Greenhouse gas
GT	Gas turbine
HRSG	Heat recovery & steam generation
IA	Implementation Agency
IEA	International Energy Agency
IET	Institute of Engineering Thermophysics
IGCC	Integrated Gasification Combined Cycle
IIASA	International Institute for Applied Systems Analysis
IOGCC	Interstate Oil and Gas Compact Commission
IPAC	Integrated Policy Assessment Model for China
IPM	Institute of Policy and Management
IPR	Intellectual Property Rights
KTH	Kungliga Tekniska Hegskolan (Royal Inst. of Technology)
LDC	Least Developed Countries
LDCF	Least Developed Countries Fund
LHV	Lower Heating Value
LIBOR	London Inter-bank offered rate
LR	Learning Rate
LSIP	Large Scale Integrated Projects
MDG	Millennium Development Goals
MDU	Malardlen University
MEP	Ministry of Environmental Protection
MLR	Ministry of Land and Resources
MMP	Minimum Miscibility Pressure
MOF	Ministry of Finance
MOST	Ministry of Science and Technology
MOVECBM	Monitoring and Verification of CO_2 Storage and Enhanced Coal Bed Methane
NAPA	National Adaptation Programmes of Action
NDRC	National Development and Reform Commission
NGCC	natural gas combined cycle
NGO	Non-Government Organization
NL	Netherland
NSFC	National Science Foundation of China
NZEC	Near Zero Emissions from Coal
O&M	Operation & maintenance
OECD	Organization for Economic Cooperation and Development
OOIP	Original Oil In Place
PBT	Payback Time

PC	Pulverized Coal
PR	progress ratio
PRC	People's Republic of China
PM	Particulate Matter
PV	Photovoltaic
R&D	Research and Development
R&DD	Research, Development and Demonstration
RIPED	Research Institute of Petroleum Exploration & Development
REDD	The United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
S&T	Science and Technology
SAIC	State Administration of Industry and Commerce
SAWS	State Administration of Work Safety
SC	Supercritical Coal
SCCF	Special Climate Change Fund
SCF	Strategic Climate Fund
STRACO2	Support to Regulatory Activities for CCS
$STRCO_2$	Support to Regulatory Activities for CO2 Capture and Storage
SWOC	Strengths, Weaknesses, Opportunities and Constraints
TA	Technical Assistance
TNO	The Netherlands Organization for Applied Scientific Research
TRIP	Thermal power research institute
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
URR	Ultimately Recoverable Reserves
US	United State
USA	United States of America
USC	Ultra-Supercritical Coal
USD	United States Dollar
VAT	Value-Added Tax
WBCSD	World Business Council for Sustainable Development

KEY FINDINGS:

1. Carbon capture and storage (CCS) is one of the important options to reduce cost for greenhouse gas mitigation in the future energy development in China. CCS development is still at its early stage globally and more demonstration proof is needed to convince the general public and the public/private sectors that CCS is a viable and mature option in dealing with carbon emissions issues.

2. The CCS project roadmap developed in this project can be used as a first order guideline. The implementation of a CCS demonstration can be divided into seven phases. The guideline includes a comprehensive list of key working activities, to provide operators of CCS demonstration projects in China with a realistic and beneficial checklist from which to begin taking actions.

3. Since investment in a CCS demonstration project is financially unviable in the current situation, there needs to be some kind of government incentive to encourage motivation. There are essentially three policy tools that the government can use to assure the required return on investment in CCS related projects in order to trigger off CCS demonstration and deployment in China, i.e., manipulation of the electricity tariff, subsidization of capital cost and exemption of the income tax. How all the incentives are going to affect a CCS project depends on an optimal mixture of the various approaches in consideration of balancing different factors.

4. Multiple entities with complementary expertise should join efforts in order to manage the full CCS chain for demonstration projects. The early commercial projects have combined the expertise of multiple stakeholders and thereby distributed risk because each partner has something specific to offer. Individual enterprises lack the comprehensive knowledge and technical capacity to conduct a fully integrated CCS project. The project will require a multitude of actions to be carried out by a diverse group of stakeholders including many functional branches of government in order to implement the full project.

5. An integrated gasification combined cycle (IGCC) with CCS has feature for the reduction of cost and energy penalty compared with a pulverized coal power plant with CCS when the installation capacity is increased.

6. The equipment manufacture and localization are the key factors for the cost reduction of IGCC with CCS. Gas turbine and gasification unit are the top two units in terms of localization potential, and their contributions account for 80–90% in the whole cost

reduction of IGCC resulted from localization. Due to the lower energy penalty and efficiency improvement, IGCC with CCS will supply main power supply in the future.

7. Criteria for assessment of CO2 geological storage in reservoir and saline aquifer, Dagang Oilfield complex have established according to the properties of the geological storage, including depth, fault sealing, exploration degree, rock properties and sealing， etc.

8. According to the geological analysis carried out for the Dagang oil field complex for this project, There are six sites suitable for CO2-EOR based on published data. Miscible and Immiscible CO2 flooding would be required for CO2-EOR. During CO2-EOR, CO2 would be lost or effectively stored underground. Following CO2-EOR, the depleted oilfield could also be used for storage. Saline aquifers near these oil fields were also considered or storage, and have considerably larger storage potential (an estimated 38 – 55 Mt based on irreducible water saturation between 10 to 40 %). From the view point of source-sink matching, CO2 emitted from IGCC could be stored for 30-50 years in the assessed fields. The distance between Greengen phase I IGCC power plant, and the assessed sites is 100 to 150 km.

9. The main bottleneck in conducting an integrated CCS demonstration lies in identifying an appropriate storage site. The primary necessity for any CCS project is identifying a suitable storage site, whether for saline aquifer storage or EOR. Characterization of the proposed storage site is the most important step to enable a CCS project to be operated safely and successfully. While site characterization begins in the early stages of a CCS project, international experience shows that it is an iterative process requiring not only time to collect, process, and model subsurface data but also special technical expertise in various sub-specialties of geology, reservoir engineering, well drilling, and more.

10. There are a series of technical, institutional, legal, regulatory, and financial gaps to be filled either before the demonstration project or in the process of implementation. Chief among these are proving reliable and continuous operation of the IGCC plant itself, developing adequate skills in storage site characterization, classifying CO2 as a substance and establishing basic regulations for its capture, transport, and storage and determining the long-term management plan of the storage site.

11. Tools and methodologies associated with CCS are of importance for the demonstration and implementation of CCS in China. Baseline measurement and sampling are essential before CO2 injection begins. There are no standard monitoring tools or methodology that has been deemed necessary for every site. The modeling ability and techniques of underground CO2 flow should be established and applied before CO2 injection.

12. From the SWOC analysis, the following findings have been identified at both the national and project level. At the national level, both challenges and opportunities exist for CCS in China as an option to reduce its growing GHGs emissions. Opportunities mainly come

from three aspects: CCS as a new option for China's CO2 mitigation technology toolbox, as a major CER supplier in international market; and as an important opportunity for involvement within international technology research and development. Challenges mainly come from the following aspects: failure of a comprehensive international agreement; contraction of the international carbon market due to cessation of second commitment period of Annex I countries; and competition with other mitigation options. At the project level, the scale of a CCS demonstration project and transportation options are largely determined by the scale of selection of storage site and ways of utilization of captured carbon dioxide. The CCS value chain should be regarded in an integrated manner where strength, weakness, opportunities and constrains should be considered as a whole.

MAIN RECOMMENDATIONS:

1. China needs to conduct one or more integrated CCS project in order to master this strategic technology. An IGCC-CCS demonstration ought to be one of the earliest starting choices. The scale of CO_2 capture and storage should be large enough to achieve relevant experience. The project suggests the planned IGCC-CCS demonstration be about 1 Mt per year.

2. It is strongly recommended that an electricity tariff of RMB 0.56/kWh, which was theoretically applied to the Greengen Phase 1, remains as the lowest level of electricity tariff to CCS related power plants. Under this circumstance the best economic situation of course is that the demonstration project can sell its captured CO2 to an oil field for EOR. The price of CO_2 could be less than $10 per tonne. However, this approach is unsatisfactory in the sense of full carbon storage. An optimal choice would be that the government raises the tariff by 20-30% from the current IGCC tariff, with the aim to cover the energy penalty caused by CCS. Meanwhile, the project also gets grant financing from international climate change related funds to subsidize the additional part of the initial capital cost. Tax exemption or tax reduction during the operation, if properly conducted, shall further facilitate mitigation of the financial burden.

3. The project strongly recommends (at least) the first demonstration project should be a coordinated national program, conducted by a consortium of complementary partners led by a pioneering company like Greengen with government support and the learning and experience gained during demonstration will be made available for all interested enterprises. Chinese enterprises have started taking action in CCS research and development. However, there is an absolute necessity for strong government leadership to form a national CCS consortium. A demonstration project should be a horizontally integrated project along the CCS value chain in order to combine strengths and substantially reduce weaknesses. Such integration could be achieved through either signing long-term contracts among participating companies in capture, transportation

and storage along the CCS value chain or establishing a joint venture among shareholder companies to share risk among different companies. International cooperation shall be encouraged for the first demonstration project.

4. China should act quickly in establishing the comprehensive capacity to conduct site characterization and storage operations and in identifying appropriate storage sites. There is an urgent need to identify appropriate storage sites as soon as possible because site characterization is very time intensive and positive results are not guaranteed. China currently has related specialists scattered across different sectors, but to be efficient in site characterization, China should organize its experts and foster specific capability in site characterization, especially in developing capabilities for subsurface geology and CO_2 plume modelling and monitoring. Because geological information for many regions of China is sparse, initial CCS demonstration projects should limit their search of a storage site to locations with good, pre-existing information in order to cut costs and save time. For GreenGen project, one of the fields in Dagang complex (Storage site E) is considered as a suitable storage site based on the location, storage potential, population density, local infrastructure and other parameters. More geological and geophysical data are necessary for more detailed study. Other candidates of storage sites could also be considered for the further investigation such as the nearby Huabei, Shengli and Liaohe Oilfields.

5. The specifications for the first IGCC-CCS demonstration project recommended by project are: (1) The plant should be designed with the freedom to be either a pure IGCC plant or IGCC plant with polygeneration; (2) A capture rate of at least 60% with the ability to reach 90% as necessary to realize the megaton-scale capture objective but not overburden plant operation costs; (3) CO_2 should be transported from the IGCC plant to the storage site via CO2-specific pipelines; (4) CO_2 handling facilities and pipelines should be designed to handle a flexible range of impurities. Special attention for R&D should be paid to location of key equipments including gasification, CO2 separation and gas turbine, whose cost may cut down significantly. Meanwhile, the policies specific for promoting the technology transfer, independently develop, and technology demonstration should be issued, which will finally drive the decarburization of coal relied power industry of China.

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

1. BACKGROUND AND OBJECTIVES

In China, the government has wisely recognized the inherent risks and environmental consequences associated with such a vast increase in power generation and the critical importance of the interrelated issues such as energy security, energy efficiency improvement, renewable energy, and environmental protection. For example, the Government's 11th Five-Year Plan (FYP) and the 12th Five Year Plan under the preparation have emphasized a resource-effective and environment-friendly balanced society. Advanced clean coal power generation technologies, including integrated gasification combined cycle (IGCC), in addition to implementation of ultra-supercritical steam power generation technology, are being developed for future implementation as a means of further increasing the thermal efficiency of power plants in China. Furthermore, CO_2 emission mitigation in coal fired power plants to tackle global climate change calls for even further steps to integrate carbon capture and storage (CCS).

CCS could provide a key, low carbon option for coal-based industry in China, particularly for power generation, which would enable the continued use of coal with very much reduced greenhouse gas emissions. At the same time, there are several challenges that need to be addressed, particularly to indentify the strategic role of CCS technology in China, to reduce the extra costs and energy penalty of CCS technologies, and to establish in sufficient detail the national capacity for CO_2 storage. The first step to face these challenges is to build one demonstration project in China, which will be a starting point for the future development and deployment of CCS technologies in China.

To support a roadmap for the demonstration of CCS technologies, the Asian Development Bank (ADB) with national executive agency (EA), The National Development and Reform Commission (NDRC), and Implementation Agency (IA), GreenGen, undertook ADB TA Project 43006-PRC: CO2 capture and storage demonstration-Strategic analysis and capacity strengthening, for a China-specific study to comprehensively analyze the current technical, financial, and policy conditions relevant to the CCS demonstration project. The aims of this project were to provide a view of the present level of preparedness for a a CCS demonstration, to identify gaps in technological. scientific, regulatory readiness, to provide

capacity building in all aspects of the CCS chain, and to develop a roadmap for CCS demonstration in the PRC.

This report presents the results from an intensive one-year study to provide specific analyses and recommendations for a CCS demonstration roadmap in China which included the following activities:

- review and assess the current status of worldwide CCS activities to provide lessons-learned and experience for the future development and demonstration of CCS in China;
- propose possible engineering guidelines with detailed steps for the implementation of a CCS demonstration project;
- identify critical gaps, barriers, and associated risks in technical, institutional, legal and regulatory aspects;
- recommend criteria for assessment of carbon capture technologies, and storage capacity to identify priority of demonstration sites and financing needs;
- assess institutional capacity and identify measures to strengthen capacity and public understanding and outreach activities.

2. CARBON MITIGATION SCENARIOS AND THE ROLE OF CCS IN CHINA – CCS WILL ENHANCE THE REDUCTION OF LOCAL POLLUTION IN ADDITION TO GHG EMISSION REDUCTION

2.1 Scenarios Modeling of CCS Technologies

In order to understand the future roles of CCS in China, scenarios have been modeled by using IPAC (Integrated Policy Assessment Model for China) including various advanced power generation technologies, such as supercritical and ultra-supercritical coal fired plants, integrated gasification combined cycle (IGCC), IGCC with fuel cells, and natural gas based combined cycle (NGCC) with CCS. The analysis on future CCS development shows great potential which is key to China's low carbon future. The results show that CCS is an unavoidable choice to reduce cost for greenhouse gas mitigation if fossil fuels continue to be the main furl for power generation and industry. The existing high cost for CCS would be initially offset by enhanced oil recovery (EOR), and will be then reduced as technology developed. The incremental cost for electricity tariff is limited due to the small capacity installed at the beginning, due to the policy changes, this cost is expected to increase by by several cents reaching 20 cents per kWh by 2040 to 2050. This figure is acceptable when household income increases several times during the same period. The key assumptions for the modeling and results of cost of electricity (COE) are shown in Table 1.

Table 1 Key cost assumptions and results for CCS

Investment & CO2 avoided costs	**2010**	**2030**	**2050**
IGCC, RMB/kW	11000	7000	6500
Capture, RMB/kW	3500	2300	1800
Transport, RMB/ton-CO2	40	20	10
Storage, RMB/ton-CO2	30	15	7
Cost of Electricity	**2010**	**2030**	**2050**
Coal fired power plant, UC, RMB/kWh	0.28	0.31	0.36
IGCC, RMB/kWh	0.45	0.38	0.33
Wind, RMB/kWh	0.44	0.37	0.33
Solar PV, RMB/kWh	1.30	0.51	0.34

IGCC+CCS, RMB/kW	0.73	0.61	0.52
SUC+CCS, RMB/kW	0.62	0.58	0.56

The IPAC model explores a low carbon emission scenario including the impact and role of CCS in future China energy. The cost for CCS is expected to increase the electricity price in the range of 0.15-0.25 RMB/kWh, and by 2030 the model shows average electricity price increasing to 0.03 RMB/kWh, and 0.15 RMB/kWh by 2050 as grid price. Adoption of CCS will increase electricity price, Fig. 1 presents the additional cost on top of the electricity price from the IPAC model (including all costs for CCS) which was calculated based on power generated. The additional cost is expected to be high during the first stage before 2030 due to high fixed cost and operational costs for CCS. The cost could be reduced significantly after that due to increases in power generation efficiency, lower emissions per kWh, and lower fixed cost and operational costs.

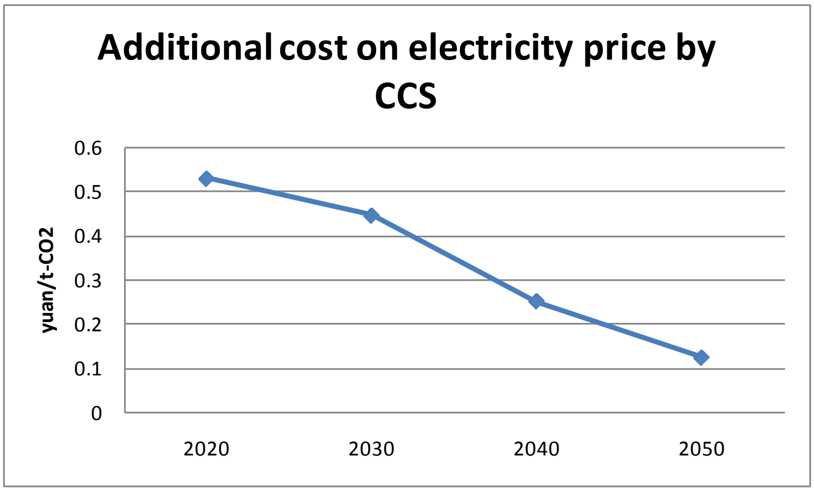


Figure 1 Additional cost on electricity by CCS

The influence of CCS on local pollutants, including sulphur oxides (SOx), nitrogen oxides (NOx), PM (particulate matter) have also been considered for the future scenarios analysis. Carbon dioxide removed by CCS is given in Fig. 2. The key assumptions are given in Table 2 and Table 3. A lower removal rate for different power generation technologies is assumed because technology development is not yet mature at the beginning of adoption of CCS.

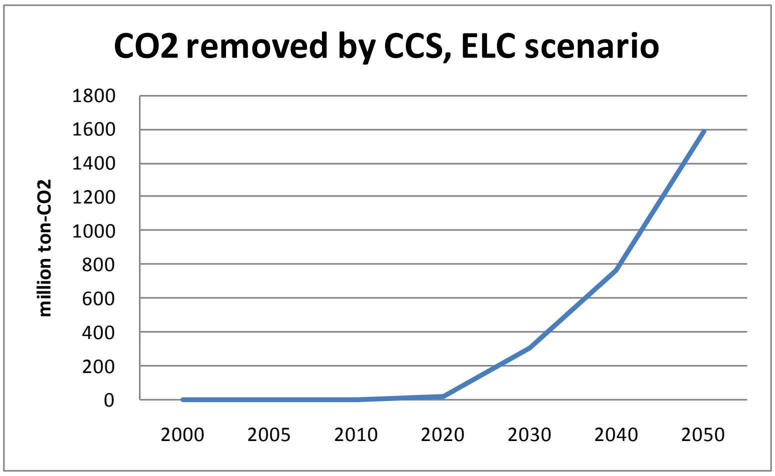


Figure 2 CO_2 removed by CCS in power generation sector

Table 2 Removal rate for CO_2 by CCS in ELC (Enhanced low carbon) scenario, %

	Super Critical	US-Critical	IGCC	IGCC-Fuel Cell	NGCC
2020	80.0	80.0	85.0	85.0	85.0
2030	85.0	85.0	90.0	90.0	90.0
2040	85.0	85.0	90.0	90.0	90.0
2050	85.0	85.0	90.0	90.0	90.0

Table 3 Power generation capacity (MW) with CCS in ELC scenario

	Super Critical	US-Critical	IGCC	IGCC -Fuel Cell	NGCC
2020	0	0	1316	0	203
2030	217	379	6310	701	3411
2040	1319	2184	12890	2275	9679
2050	2822	8465	22045	5144	21514

2.2 Local Environmental Benefits by Implementing CCS

Use of CCS will increase energy use, and therefore, could increase local environmental pollution in general. However, IGCC with CCS could contribute not only to greenhouse reduction but also improved local environmental effects than other coal fired power generation technologies with CCS. Key environment pollution by IGCC is given in Table 4.

Table 4 Environment effects from IGCC power plants

	IGCC	Note
SO2	Removal rate>99%	
NOx	25mg/m3, removal rate > 90%	70% to 85% less than PC plants
PM	1-2mg/m3	
PM2.5	0.3-1mg/m3	
Mercury	5ppmw	Removal rate>90%
Water used	30% to 50% less than PC plants	

The impact from CCS essentially does not have much of a negative impact on total SO_2 emissions due to the already superior emission performance of IGCC. However, there will be some increase for SO_2 emissions from USC+CCS (ultra-supercritical coal with CCS) and SC+CCS (supercritical coal with CCS) in the early stages, but not at a large amount (错误！未找到引用源。).

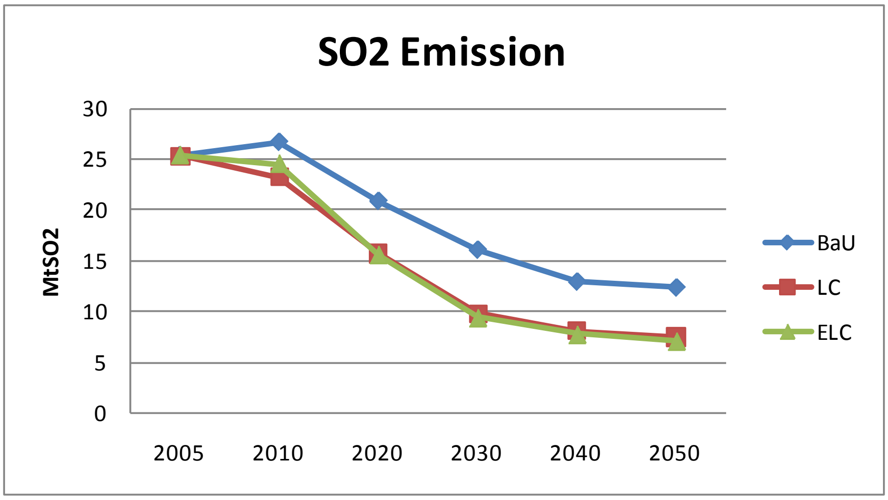


Figure 3 SO2 emissions in China from energy activities from the IPAC model

Use of CCS will increase fuel use for power generation, which could have a negative impact on energy security. It is predicted there will be additional 147 million tce (tonnes coal equivalent) energy used for CCS in China by 2050. However, the negative impact on energy security could be abated by further use of high efficiency power generation technologies such as IGCC. Without CCS, it is expected that fewer IGCC plants will be built, and without this widespread deployment, that the efficiency of IGCC will not improve as significantly.

2.3 Future Power Generation with CCS

How much CCS will be used depends on emission reduction requirements. Fig. 4 gives CCS in the enhanced low carbon scenario from the IPAC model, which will require deep cuts on CO2 emissions after 2030.

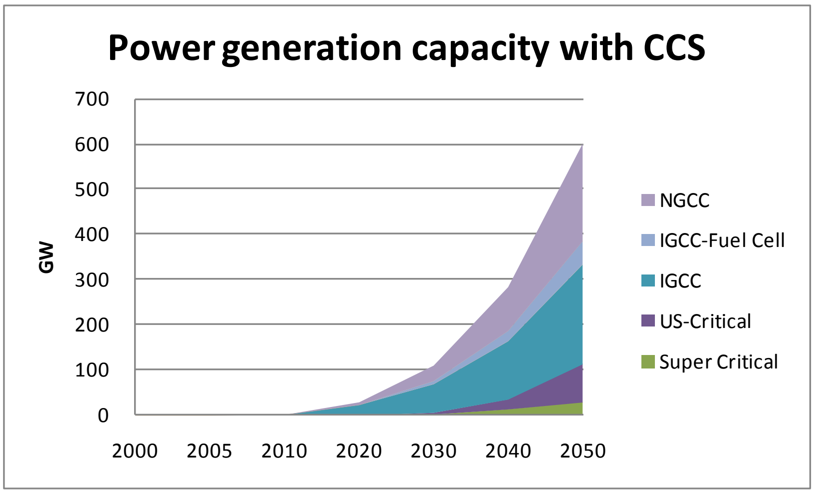


Figure 4 Scenario of installed power generation capacity with CCS in China

China is looking for a new direction for economic development. Technology innovation and national competitiveness by high technological pioneering are becoming one of the key components for economic growth. Recent rapid expansion of advanced high efficiency technology exports for low carbon technologies development has become highly attractive. CCS is getting the attention of Chinese manufacturers for possible future markets. In contrast to renewable energy technologies, manufacture of CCS technology requires larger scale of manufacturing activities and research activities. This might attract industry in power generation and oil sectors to become more interested in CCS.

3. STATE OF THE ART: INTERNATIONAL CCS DEMONSTRATIONS AND R&DD IN CHINA

3.1 International CCS Demonstration

Based on the statistics of the Global CCS Institute[1], there are total 328 CCS projects in the world, including 31 completed, 39 cancelled projects and 238 active and planned projects (of 151 are classified as integrated projects with whole chain of capture, transport and storage, including 80 large scale integrated projects -- LSIPs). Among the LSIPs, only two projects are in the "execute" stage and 8 are under the "operational" stage. Four of eight projects are common EOR industry practices and are not solely for the purpose of CO_2 storage. The other four projects, namely, Sleipner, In Salah, Snøhvit and Weyburn, are integrated capture and storage commercial projects, although none use CO_2 captureed from coal-fired power plants as their CO_2 capture source. Whereas the CO_2 captured by the three former projects are disposed of in saline aquifers and the Weyburn project injects 2.8 Mtpa CO_2 for EOR. This implies that CCS development is still at its early stage globally and more demonstration based proof is needed to convince the stakeholders for confident investment and public acceptance. From the international experiences and practices for the implementation of CCS project, several issues shall be considered for China's demonstration, for example, identification and characterization of storage sites and capacity in China which calls for both fundamental scientific studies and engineering field tests, cross-sector cooperation among different industrial sectors and coordination of stakeholders through the whole chain of CCS.

International joint activities on CCS involve multi- and bilateral cooperation focused on R&D of technology, intuitional arrangements, as well as legal and regulatory issues. Table 5 lists the projects, objectives and partners. Projects have covered various aspects including capture, transport and storage of CO_2. In addition, all activities are short term and project based, which results in little following up activities of updated development. A network or platform for CCS in China to enhance knowledge sharing among the different projects is

[1] GCCSI, The Status of CCS Projects Interim Report 2010

suggested. This will be helpful for the dissemination of R&D results as well as avoiding the repeating R&D efforts among various projects.

Table 5 Summary of International Cooperation Projects in China

Project	Objectives	Partnership	Finance	Duration/status
NZEC[2], CO_2 Capture R&D Project, Integrated Systems Demonstration Project	Explore options for the demonstration of CCS applied to a coal power plant in China; Build knowledge and capacity on CCS in China.	UK: AEA and 7 other partners; China: ACCA21[3] and other 19 partners	UK Department for Environment, Food and Rural Affairs (Defra); UK Depart. for Business, Enterprise & Regulatory Reform (BERR); China MOST[4]	2007. Phase 1 (feasibility) ended in 2009. Phases 2 and 3, expected late 2009 until at least 2015
COACH	Establish broad cooperation between China and the EU in CCS; provide technical recommendations for designing a coal-fired power plant with CCS	20 partners (R&D, Manufacturers, Oil&Gas companies, etc), 12 from Europe and 8 from China	European 6th Framework Programme	2008-2010
STRACO2, Support to Regulatory Activities for CCS	Research regulation frameworks for CCS and GHG control	MDU, KTH, WBCSD[5], DS, TNO, ACCA21, CAS IET, CAS IPM.	European 7th Framework Programme	From January 2008 to the end of 2009
CCCDP, China-Canada CO2-ECBM R&D Project	Lead to a demo. project in China; produce an inventory of suitable coal beds, a detailed site selection process, micro-pilot & large scale testing, evaluation and training exercises	CUCBM6, Alberta Research Council, Cal Frac Well Services, Computalog, Computer Modelling Group, Porteous Eng., SNC Lavalin, Sproule International	Phase I–Canadian $10 million, CUCBM and other project partners; Phase II–Canadian $60 million	Phase I: March 2002 to March 2007; Phase II: preparation
China Australia CAGS Project	accelerate develop. & deploy. of CCS in China and Australia; Capacity building; environmental impacts and risk assessment	Geoscience Australia, MOST, ACCA21, CAS, China Univ. of Petroleum, China Geological Survey	Au$2.86 million, supported through the Cleaner Fossil Energy Task Force of the Asia Pacific Partnership on Clean Development and Climate	2009-2011

[2] NZEC, Near Zero Emission Coal
[3] Administrative Centre for China's Agenda 21
[4] MOST, Ministry of Science and Technology, China
[5] World Business Council for Sustainable Development (WBCSD)
[6] China United Coal bed Methane Corporation

CAPPCCO, Chinese Advanced Power Plant Carbon Capture Options	develop and assess capture options for new PC plants and existing PC plants	UK: Imperial College London, Univ. of Cambridge, Doosan Babcock, Alstom, CHN: Harbin Inst. of Tech., National Power Plant Comb. Eng. Tech. Center, Harbin Boiler Comp. Ltd. , Yuanbaoshan Power Plant, Datang Internat. Power Generation Co. Ltd, Xi'an Jiaotong Univ.	Total £335,131, Department of Energy & Climate Change (DECC) contributes £264,904	December 2007 to July 2011

3.2 Industry Activities in CCS R&DD in China

Industry sectors from power generation, oil and gas, and coal producers, such as GreenGen (Huaneng Group and other utility companies), Shenhua Group, and PetroChina, are actively involved in CCS RD&D. Some demonstration projects on a relatively small scale have been implemented, see Table 6. Similar to the international cooperation projects, the coordination among the industrial sectors shall be enhanced. Knowledge sharing and transfer through different sectors, for example, expertise from power generation sector in CO_2 capture, and competences from oil and gas industry with regard to storage, can be realized through cross-sector cooperation. This is especially important as a CCS project requires joint efforts from different stakeholders along the whole chain of processes including capture, transportation, and storage.

Table 6 Summary of Enterprises' Activities in CCS in China

Project	Technology	Partnership	Finance	Duration/status
GreenGen Corporation	IGCC Pre-combustion capture Gasification or partial oxidation shift plus CO_2 separation	Huaneng with 7 state-owned energy companies: China Datang Group, China Huadian Corporation, China Guodian Corporation, China Power Investment Corp. , Shenhua Group, State Develop. & Invest. Corp. , China Coal Group	Registered capital: RMB 300 million(about USD 44 million) Huaneng 51%, and other 7 in the group 7% each. Total Investment will reach RMB 7 billion	Phase Ⅰ:2006-2009 Phase Ⅱ:2010-2015 Phase Ⅲ:2016-2020
Shenhua CTL	Coal to synfuels (direct coal liquefaction); saline aquifer storage	Shenhua Group, Sasol, West Virginia University	USD 1.4 billion	started in late 2009
Huaneng Beijing Thermal Power	Post-combustion capture; research project by CSIRO	Huaneng, Australia CSIRO, Thermal Power Research Institute	USD 2.95 million	Operational since July 2008

pilot project				
Pilot program in Jilin oilfield	EOR, CO_2 from natural gas	PetroChina	RMB 200 million	testing

4. GUIDELINE FOR THE IMPLEMENTATION OF CCS DEMONSTRATION PROJECT – CCS DEMONSTRATION ROADMAP

4.1 7-Phases Implementation of CCS Project

A CCS demonstration roadmap in this study is defined "to provide conceptual instructions and/or guidelines to foster government initiative and facilitate project implementation in the near future" in China. Referring to the procedures for implementing a conventional energy project with the additional special considerations of a CCS project, a 7-phase implementing procedure for a CCS demonstration project was developed in this project. This procedure consists of preparation, feasibility study, appraisal & approval, implementation, operation & monitoring, evaluation & closure, and post-closure management as shown in Fig. 5.

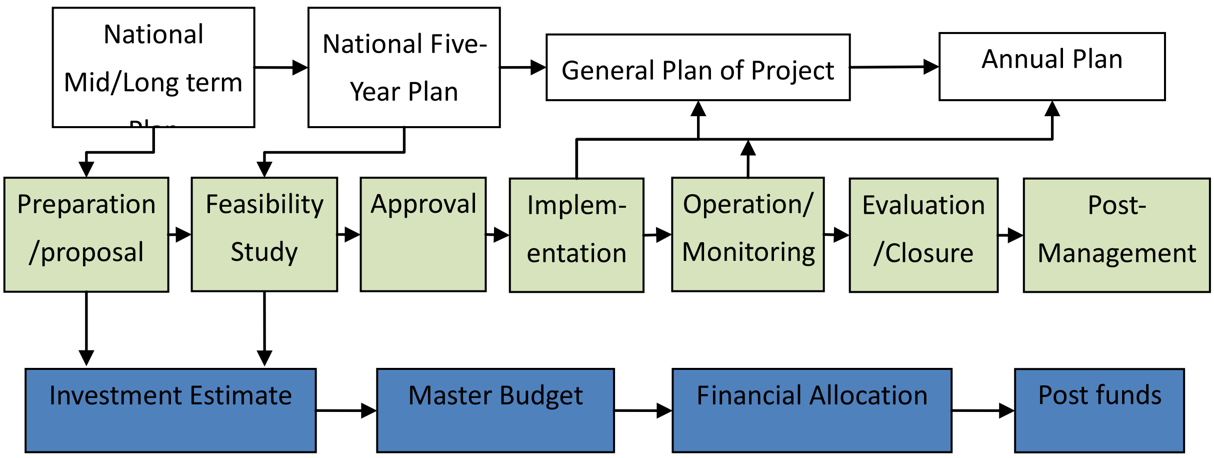


Figure 5 7-Phase implemention procedure for a CCS demonstration project

4.2 Definition of contents of 7-Phases project implementation

The contents and duration of each phase may vary according to the specific conditions of the project and certain actions may need to be repeated in later phases due to unforeseen

changes in regulations, early geological assumptions, etc. Table 7 presents the contents of each phase for the implementation of a CCS project and potential stakeholders which might be involved in the project development phases. It shall be noted that the duration of each phase is estimated (with detailed information available in the subreport of work package of this project), as no experimental data are available in China. It might be possible to shorten the lead time if previous input data were available. For example, the time for the feasibility study can be significantly reduced if available geological data are available for the carbon storage. Detailed discussions on the guideline were presented in subreport WP1, the first working package of this project.

Table 7 Definition of contents of each phase for the CCS project

Phase	Descriptions	Stakeholders
Preparation	- Perform preliminary study • *background information to be fully aware of topic* • *potential technical pathways* • *preliminary analysis on potential capture sources, storage sites, and available technology* • *risk/liability* • *Stakeholders consultation on FS Report* • *business partners and organization structures* • *limitations of the project* - Pre-feasibility report & proposal for permission - Approval of advancing to Feasibility Study	Project developer, national authorities (e.g. NDRC, MOST), investors
Feasibility Study	- Establish or entrust an executive agency - Entrust the consultant agencies - Convene project starting workshop - Capture-related feasibility study • *Survey and select a capture site – i.e. brown vs. Greenfield, national to local location, etc* • *Survey and Select plant type – IGCC, Post-Combustion coal power, NGCC, CTL, Coal Chemical, etc.* • *Research and decide on capture specifications and conditions – capture rate, capture technology, CO2 purity, etc.* - Storage-related feasibility study • *Regional survey of potential storage areas and select location(s)* • *Initial storage site geological characterization – subsurface mapping, geo models, injectivity estimates, containment estimates, capacity estimates from old data and new well logs, cores, and seismic imaging, or others.* • *Storage plan - EOR vs. Saline Aquifer, storage capacity, CO_2 composition and*	Project developer, engineering firms, investors, government authorities, public

pressure standards

Initial economic estimates, risk assessment (including existing well and fault identification), monitoring plan, and remediation plan

- Transport-related feasibility study

- *Source-sink matching between selected &/or potential capture and storage sites to select optimal pair and potential routes*
- *transport method: pipeline vs. ship vs. truck*
- *Regulation issues on transport requirements – CO_2 purity, pipeline materials, spacing of emergency shut-off valves, max/min pipeline pressure, pipeline burial depth, type of warning system, etc*
- *Transportation technology and materials*
- *Route design for pipeline*

- Environmental feasibility study

- *Assess environment impacts of CCS chain*

- Public acceptance feasibility study

- *Public communication and consultations*
- *Knowledge awareness promotion together with gov't.*

- Economics & Financial feasibility study

- *Cost estimates for best/worst/expected case scenarios – includes capital survey, characterization, & construction costs, increased cost of electricity, cost of injection, cost of accident remediation, cost of operation and maintenance, monitoring, etc.*
- *Cost-benefit assessment of the project*
- *Financial evaluation of resources necessary to operate the full project and manage post-operation costs as well as cover "insurance" in case of accidents*
- *Evaluate possible financing sources and reach out to identified financiers*
- *Prepare project investment plan and statements*

Prepare financial letters of intent from all financiers

- Project management & business organization structure

- *Formation of the project owner & developer/operator*
- *Organizational chart, employment predictions, and training programs*
- *Measures to take for worker protection, health, and safety*
- *Implementation/project plan*

- Legal & regulatory feasibility study

	• *Study policies for CCS internationally* • *Examine existing laws for applicability* *Recommend policies needed from policy makers in order to make the project and subsequent projects viable* - Compile and present feasibility study report	
Appraisal & approval	- Form independent project appraisal committee - Local gov't & public consultations on capture site - Assess and permit land use plan for capture site, storage site, right of way for pipeline or other transportation form route - Assess and permit environment impact analysis report - Approvals of water consumption for plant and water protection at the pipeline and storage sites - Approval from government agencies for financial assistance， foreign capital investment， loan schemes from banks， etc - Issue special regulations or policies to fill in for legal and regulatory gaps - Form independent regulatory institution - Establish business and/or prepare business license & registration - Organize and supervise signing the letter of intent or contracts between main stakeholders - Issue licence for project design and construction	Project developer, third party assessor, government authorities
Implement-ation	- Establish project headquarter - Entrust project consultant agencies - Secure capital and operation funds - Project preliminary design and construction document design • *Capture facilities (plant) design* • *Pipeline route (networks) design* • *Infrastructure design for storage site* • *Injection well design & injection strategy design* - Approval of construction document - Site characterization – test injections to determine "Proved Storage Capacity" sufficient for planned storage volume - Update and optimize geo and simulation models - Develop project execution plan - Cost budget & control plan - Quality assurance and control plan - Schedule control plan - Human resource management plan - Risk analysis, monitoring and control plan	Design engineering and construction companies, project developers etc.

	- Procurement and contract administration plan - Security assurance and control plan - Final accounts, audit and transfer plan - Construction and monitoring	
Operation & monitoring	- Entrust or form project operator - Transfer control rights of assets - Measurement, monitoring, and validation plan - Contingency migration and remediation plan - Detailed injection plan (timing and staging) - Surface and groundwater monitoring plan - Stream purity, dehydration and corrosion control plan - Caprock, surface bulge, seismic activity and CO_2 plume monitoring plan - Operational logging and data collection inform operations plan - Geological model updating and implementation change plan - Regularly report on financial, technical, risk analysis, etc	Project developer and owner, engineering and construction companies, government authorities
Evaluation & closure	- Propose project closure proposal - Convene independent assessment committee - Conduct comprehensive environment safety and human non-endangerment assessment - Conduct long-term risk assessment of storage site - Conduct subsurface assessment for wellbore integrity - Conduct well plugging and abandonment feasibility assessment - Conduct assessment on post-monitoring, maintenance, contingency migration, and remediation plans - Entrust or form long-term administration entity - Record and register project lifetime data to public database - Transfer assets and responsibility from operator to long-term administration entity - Certification of site closure	Project developer, operator, storage site monitoring and management firms, government authorities etc
Post-closure management	- Make and execute monitoring, maintenance, contingency migration, and remediation plans for the closed site - Conduct periodic measurement, monitoring, validation of closed site - Record and register site monitoring data - Long-term funding management and new mechanism development - Research on geological reuse of the closed site	storage site monitoring and management firms, government authorities etc

5. CHARACTERIZATION OF IGCC WITH CCS AND CAPTURE RATE FOR THE DEMONSTRATION PLANT

5.1 IGCC and IGCC Based Polygeneration Systems

IGCC based polygeneration has been selected as potential technology for the integration of CCS in this project. The system boundary with feedstock and external products has been defined as shown in Fig. 6. The *internal dimension* will be designing the plant (i.e. the IGCC-CCS plant) to meet the performance and operational conditions, level of integration, automation and boundary limits etc., as well as economic parameters. The *external dimensions*, will include: 1) The fuel supply (availability of feedstock and logistical chains therefore) , 2) market for electricity (grid connection), 3) options for heat integration (primarily optional CHP (combined heat and power) mode or integration with adjacent industry), 4) CO_2 transport and storage (i.e. distances to sink, potential use of CO_2 (EOR/EGR) or disposal (in deep-hole geological structures), 5) market for additional yields (synthetic fuels and/or chemicals provided polygeneration is employed), and 6) a sub-set of societal aspects including the regulatory framework, economic incentives and funding issues, national and international political framework, public opinion, etc. The severity and relative importance of these dimensions will be case specific and may vary depending on whether the plant is a replacement (brownfield) or an entirely new plant (greenfield). The defined IGCC-CCS plant has been used as a reference system for the project for the technical, economic and other impact analyses.

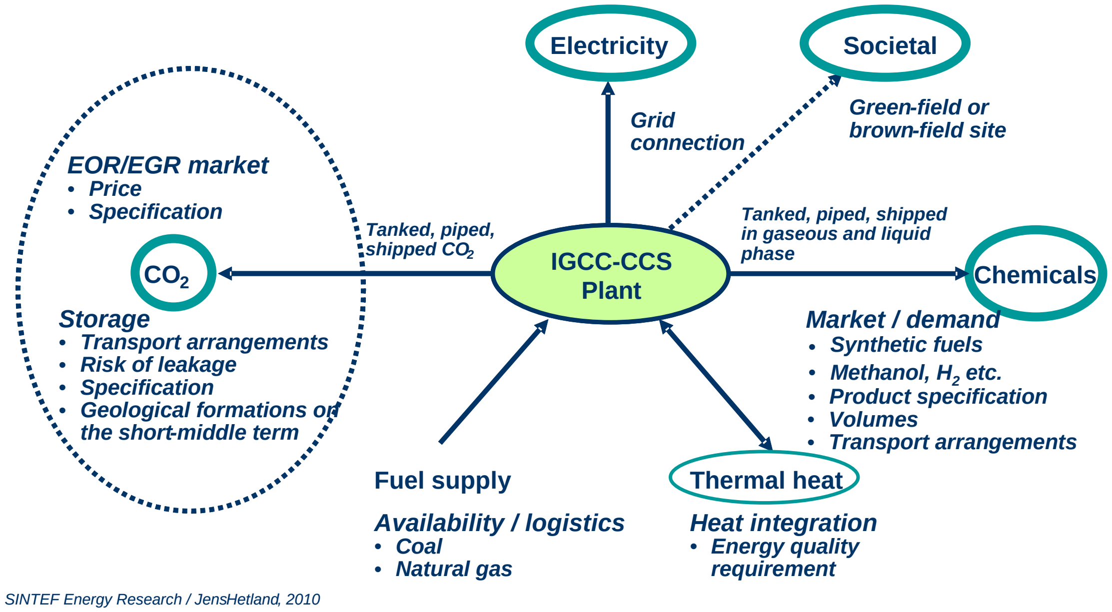


Figure 6 The framework of IGCC-CCS plant for the demonstration plant defined in this project

The technical specifications and characteristics of the IGCC-CCS plant are presented as follows:

- Power generation in the 400 MW class[7] using advanced thermodynamic cycle(s) with gas turbines in the 250-300 MW range burning hydrogen-rich gas (with fuel dilution)
- 60% or 90% CO_2 capture rate, whereof the former can be realised by partial shift reaction or by partial bypassing of shift reactors. The reason for this recommendation is because, on the condition of sufficient CO_2 capture amount, the capture rate should be flexible enough to accommodate the overall optimization of the plant in efficiency, capital cost and cost of electricity. In other words, 90% of capture rate is not a firm requirement.
- Preference should be given to a solvent based on physical absorption made up by some alcohol in order to omit (possible) problems in the hot section of the gas turbine caused by slippage of small amounts of the solvent, which may deposit on static and rotating parts of the gas turbine and cause troubles. Additives should therefore be subjected to assessment and be approved beforehand by the gas turbine manufacturer.

[7] Typically comprising a 270-300 MW gas turbine and 100-130 MW bottom Rankine cycle. From coal a 3-400 MW power generation would be suitable. For comparison the existing Buggenum IGCC is rated at 250 MW, and the Puertollano IGCC at 335 MW) whereas the new Magnum project (NL) 1200 MW in IGCC configuration and 1100 MW in NGCC configuration, and the Hatfield Colliery project (UK) 800 MW in IGCC configuration. The two latter ones had a planned availability around 86-87% in IGCC mode and over 90% as NGCC.

- The purity of the CO_2 exiting the plant shall be in accordance with specification proposed by the COACH project. Of particular importance is the water content, which should be limited to be lower than 500 ppm – preferably around 300 ppm - as the design basis due to the corrosion problem free water could cause.
- Planned availability in IGCC mode: 85%. If natural gas is an optional fuel the operational availability should be planned somewhat higher (e.g. in excess of 90%), thus, allowing the plant operator to supply power in periods of downtime needed by the gasification unit and other parts of the plant.
- The plant (at least the gasifier) should preferably operate at base-load conditions, which would allow a high degree of integration of the ASU with the gas turbine.
- The operating conditions should be further decided on whether high (but partial) integration or a full integration scheme should be pursued. It should be noted, however, that a higher degree of integration would (usually) offer higher net plant efficiency, but it would be less favourable to the operational flexibility.
- An air separation unit (ASU) of appropriate size should be chosen to accommodate the desired level of integration. Furthermore, a low specific power demand (kWh/tonne O_2) should be aimed at.
- The demand for tanked liquid oxygen must be considered (by volume) as the availability of sufficiently large amounts of liquid oxygen may a) reduce the start-up time and b) improve the operational flexibility.
- The nitrogen that is left over from the ASU should be made available at almost ambient temperature (in order to utilise its cooling potential within the cryogenic process). It should then be used for dilution in the combustion chamber of the gas turbine in order to release its pressure potential and to avoid hot-spots and thereby preventing or reducing NOx formation. The nitrogen should be delivered to the combustion chamber at a pressure around 5 bar higher than that of the high pressure compressor of the gas turbine (to overcome the flow resistance of being injected into the combustion chamber).
- The plant could be equipped with one of more interfaces for polygeneration if a swing product is required (such as either MeOH or H_2).
- The plant should furthermore allow for various coals in the range from bituminous coals to anthracite in order to improve flexibility and to test the impacts of various coal properties.

- With conventional coal (bituminous coal) the emission index will be around 130 g CO_2/kWh with 90% capture rate (CR) and closer to 420 g CO_2/kWh with 60% CR. This means that the resulting annual emissions of a 400 MWe plant will be in the range from 0.4 – 1.3 Mtpa with 90% and 60% CR respectively.
- Conversely, the amount of CO_2 to be stored will be in the order of 1.1-2.0 Mt/a, with 60% and 90% CR respectively.
- Required storage capacity over the lifetime of the project (assumed to be 50 years) amounts to 55-100 Mt CO_2, depending on the capture rate (i.e. with 90% and 60% CR, respectively). A suitable margin should be considered – for possible capacity extension of the plant in the future. This implies that a plan for disposal of these amounts of CO_2 is required.
- It should be considered if the initial phase should be fully rigged for storing all the captured CO_2 or if just a smaller part thereof should be stored in order to first gain experience from the CO_2 export system (i.e. transport, injection and monitoring).
- The required infrastructure for CO_2 transport must be addressed – including preconditioning of the CO_2 (mainly dehydration at the specified water content level), compression, piping/shipments and injection.

5.2 System Integration

Depending on how to integrate ASU with power generation island, four options can be considered for the integration of the plant, see Fig. 7:

- **No integration** means that the ASU and the gas turbine are operating as two autonomous units. They will offer high flexibility, however, on the cost of a larger overall power demand.
- **Partial integration (low)** means that the nitrogen left as a by-product by the ASU is compressed and used to dilute the combustion gases in the gas turbine. This may improve the overall plant efficiency to some (minor) extent, and it will largely offer the high flexibility of two independent operations.
- **Partial integration (high)** means that compressed air produced by the gas turbine is extracted and fed to the ASU, whereby the main air compressor of the ASU may be reduced by number of stages. Also the nitrogen is used to dilute the hot section of the gas turbine, as described above (item 2). These modifications may improve efficiency,

although the flexibility will decrease because the ASU cannot operate in full mode unless the gas turbine is operating.

- **Full integration** means that the ASU will receive all compressed air from the gas turbine, thus leaving no main air compressor for the ASU, and the excess nitrogen is used entirely for dilution of the gas turbine. This will offer higher net plant efficiency, whereas the flexibility will be significantly reduced. The gas turbine has to run in order to deliver compressed air to the ASU. This option would normally require a gas turbine that is capable of operating with dual fuel – either by natural gas as an optional fuel to coal, or by liquid fuel.

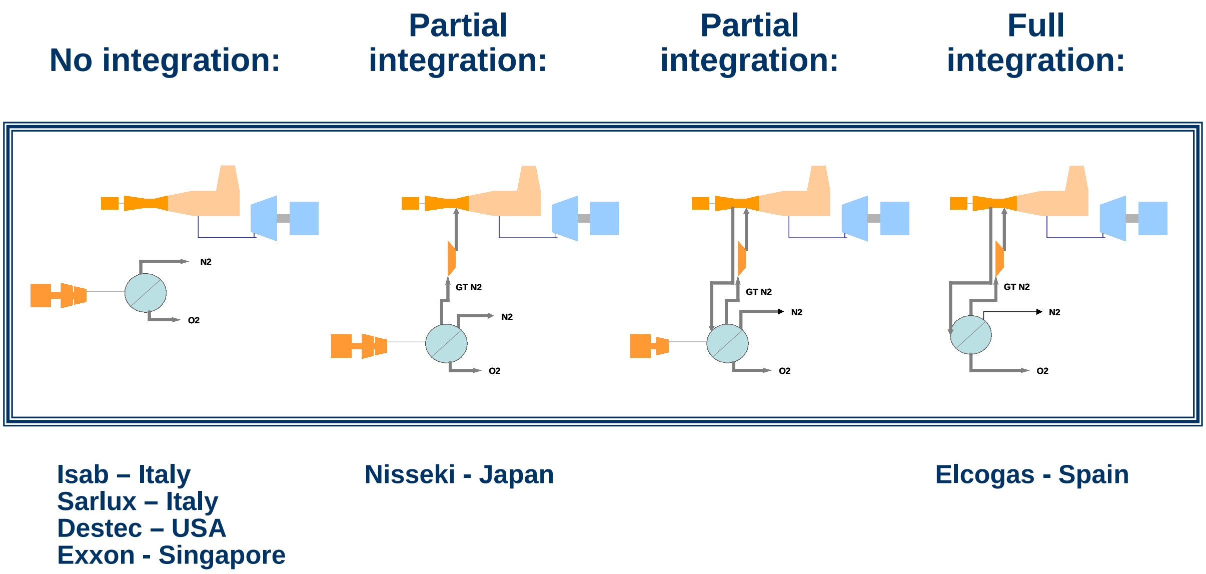


Figure 7 Integration of the ASU and the gas turbine (with indication of some actual projects)

5.3 Capture Rate of CCS

Fig. 8 shows the emissions vs. capture rate for various technologies. A natural gas combined cycle (NGCC) emits around 400 g CO_2 per kWh, whereas modern Chinese supercritical power plants with 44% efficiency emit roughly twice as much. In order for coal-based power plants to cope with the emission index from conventional NGCC, a capture rate in-between 50% and 70% is required as shown by the red broken lines of Fig. 8. This justifies a capture rate of approximately 60% which would be required to bring emissions down to the 400 g CO_2 per kWh level. A capture rate for coal-based power plants of 60% may be deemed relatively low in comparison with prevalent targets set for Western projects (i.e. usually in the order of 90%). Nevertheless, decisive factors for China are investments and cost of electricity (COE). A

high capture rate will generally drive both costs upwards. Studies suggest that these costs are prone to increase almost linearly up to a capture rate of around 80-90% (depending on system), but as the rate goes beyond 90% and approaches 100% the cost will go sky high. This explains the immediate reasoning for seeking to keep the capture rate within a level that is deemed affordable and acceptable in China.

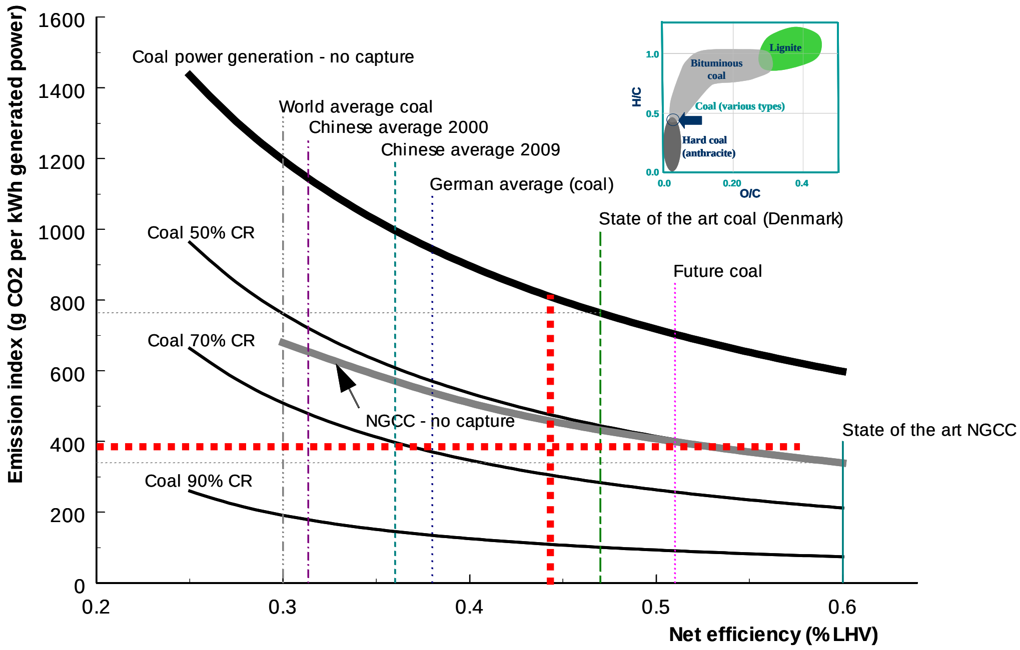


Figure 8 Emission index in g CO_2 per kWh net electricity vs. plant efficiency (LHV) from coal (solid black lines) and natural gas (solid grey line) with various capture rates applicable to coal.

Notes: Dotted red indicates the level for "clean energy" typical of NGCC (horizontal line) and the assumed net efficiency of a large IGCC without CCS (vertical line). The type of coal is as indicated in the van Krevelen diagram at the upper right hand corner of the figure.

When it comes to IGCC-CCS, one may assume that 60% capture rate is obtainable via a partial shift of the synthesis gas, which implies a cheaper shift reactor with high conversion efficiency. As the capture unit will isolate just the CO_2, the un-shifted carbon monoxide will be left with the gas stream that diverts the fuel to the gas turbine. Seemingly, this approach represents an interesting option for improving the competitive edge of pre-combustion capture processes and may prove useful in broaching CCS also into other developing

countries. Should a higher capture rate be required (e.g. 90% as in Europe) mainly the shift reactor would have to be replaced with a more complex one, and the CO_2 compressor unit may either be up-rated, or replaced by a larger unit capable of handling 30-40% more CO_2. In this way the 60% capture rate will not lead China into a lock-in position, but leave the option fairly open to adapt to stricter regulations in due course.

Furthermore, following the Chinese position from COP-15 in Copenhagen 2009 on reducing its carbon intensity by 40-42% by 2020, another justification can be derived from the fact that the global demand for primary energy roughly doubled since the early 1970s until year 2000. The doubling was (in brief) evenly shared between OECD countries and non-OECD countries. A new doubling is underway that will probably be reached by 2030-2040. This time it is expected, however, that less than 10% of the growing demand will owe to the developed societies, whereas more than 90% increase will take place in developing countries – in particular China (and India). This means that the OECD countries are not supposed to extend their power system significantly, and must, hence, cut drastically the emission index of each new plant, whereas the developing countries may obtain a relatively high reduction in its carbon intensity by imposing a new *clean energy act* on all new power plants, notably to ensure that the CO_2 index be kept within a ceiling (e.g. 400 g CO_2 per kWh). According to this approach the outcome of a 60% capture rate in China would then be 50% emission reduction from each of the many new plants that will be built or replaced in the coming years and decades.

6. SWOC ANALYSIS, TECHNICAL, INSTITUTIONAL LEGAL AND REGULATORY GAPS FOR CCS DEVELOPMENT, DEMONSTRATION AND FUTURE APPLICATION IN CHINA

A SWOC (Strengths, Weaknesses, Opportunities and Constraints/Challenges) analyses at country level and firm level have been conducted in the project in order to understand CCS from viewpoints of a national strategy and developer's benefits.

6.1 Analysis at national level

Following results from A SWOC analysis at **country Level** are concluded:

Strengths

- ***Public Funding:*** China has several portfolios of CCS research projects in place. Both the National basic research programme (973 Program) and the National high-tech research and development programme (863 Program) have allocated funding for CCS. These funding projects covered each part of a CCS project from capture to storage.
- ***Industry-Public Science Collaboration:*** An industry-public collaboration has been established in China for CCS research, development and demonstration.
- ***Global Industrial Actors:*** Some Chinese companies have acted as global industrial actors and have participated in global industrial CCS partnerships worldwide. In 2005, the Huangneng Group joined the FutureGen project as an industry partner. This has been regarded an exciting step forward into international cooperation to meet long-term global energy challenges and promote a cleaner environment and create solutions to address climate change. Chinese companies are also active in international projects. In COACH, NZEC and other international projects, Huangneng, Datang, PetroChina and Shenhua are active industrial partners.
- ***Demonstration Projects:*** There are already several CCS pilot and demonstration projects, which are in the implementation or planning phase in China. The experiences from those projects will be useful for the first IGCC-CCS demonstration plant in China.
- ***No Major Changes for Existing System:*** The energy supply in China is mainly based on coal. The situation is unlikely to change the foreseeable future. Currently, the China

Huaneng Group accounts about 92% of coal-fired power generation. One of the important tasks of the Chinese power industry is to improve the generating efficiency of coal-fired power generation, reduce the specific coal consumption and thereby the CO_2 emissions resulting from the harnessing of coal. CCS will need no major fundamental changes to current energy supply and power generation systems to achieve the goal of a significant CO_2 emissions reduction. The major obstacles will be the increase in the cost of electricity, the increase is fuel consumed due to the energy penalty, and furthermore, an infrastructure for CO_2 transport will be required.

Weaknesses

- ***High Mitigation Cost and Energy Penalty:*** The higher energy penalty and generation cost will be a major barrier for CCS compared with other alternative technologies. The investment cost for nuclear power, offshore wind power, PV, SC/USC with capture and IGCC with capture are assumed as 1500 US$/KW, 1500 US$/KW, 2000 US$/KW, 1100 US$/KW and 1300 US$/KW by 2050 respectively. The energy penalty for capture is assumed to be 10% for SC/USC and 8% for IGCC respectively. Further reduction in the investment cost for these key carbon abatement technologies and reduction in the energy penalty for CCS is crucial to reducing the marginal abatement cost. Cooperation between developed and developing countries as well as financial and technology transfer from developed to developing countries should be encouraged to further research, develop and demonstrate these advanced technologies including CCS.

- ***Low Policy Priority:*** Although CCS is an important choice in mitigation package, it is still not in the priority list in China's policy. The potential importance of CCS in China is highlighted by the rapid economic growth accompanied by rapid energy and electricity demand, and plentiful coal reserves. China also announced its emission reduction target to reduce its carbon intensity per unit of GDP by 40%-45% in 2020from 2005 level. CCS will be an important choice which could help China achieve and even enhance such voluntary commitment. In the near term, as announced by the Chinese government, the priority for China's energy development is still energy conservation and development of new and renewable energy sources. However, CCS offers an important strategic option for future carbon mitigation if CO_2 concentration in the atmosphere has to been stabilized to be at 550 ppmveq or even lower. Two significant obstacles for CCS development exist, one is its relatively high investment cost, the nother is the energy

penalty, which would put higher pressure on coal supply. It is very important to demonstrate CCS through international cooperation to overcome these obstacles.

- ***Lack of Collaboration along CCS chain:*** CCS is an integration of different technologies in different areas. The maturity of CCS technology will depend on maturity of technologies in these areas. Thus the market for relevant applications in the CCS chain from capture to transport and storage will determine the market for CCS as a whole.

- ***Lack of Guidance and Regulations:*** Several regulatory frameworks on CCS have been or are in the process of being developed worldwide. These frameworks mainly focus on regulating CO2 storage. All emerging regulations are similar in that they focus on issues related to exploration and storage permits, site characterization, risk assessment, monitoring and verification requirements and post-closure liabilities and financial responsibility. One of the barriers to the deployment of CCS projects in China is the lack of regulatory experience with underground injection specific to CCS. One option for China is to focus its efforts on developing CCS technology to reduce costs and energy penalties, before addressing policy and regulatory barriers. Alternatively, regulation can be developed in advance or in parallel to facilitate the deployment of CCS technology. Currently China lacks a comprehensive regulatory framework on capture, transportation and storage of carbon dioxide.

Opportunities

- ***Early Action:*** Under the current climate regime (Kyoto Protocol), China is categorized as a developing country and has no quantified emission reduction target. There is increasing international pressure requesting china a greater commitment to control its carbon emissions. Although there are quite different views about what kind of commitment taken by China would be a fair contribution to the global efforts, it is for sure that China will take more and more responsibility in climate change issues. One scenario is China will peak its emission around 2040 and then begin reduce this emission after that. If the global long-term target is even tighter, china will have to peak its emission even earlier. Such scenario will be a huge challenge for China, given its fast growth of economy and lagged transformation of energy system. In this situation, early action will help China to transform its energy system smoothly and cost effectively. CCS is one of many options could help China change its energy system, especially coal-based power generation system to a low carbon path.

- ***International Finantial Support:*** International funding for CCS is crucial to the realization of CCS at scale in China. International funding could give financial support to CCS projects through various channels. CDM (Clean Development Mechanism) market is one of the leading channel to help developing countries reducing their emissions. Unfortunately but the current CDM regime is not well matched to the CCS project largely due to political disagreement among Parties. There are other channels such as specialized funding which can be used as the financial resource to provide necessary funding for CCS project. This international funding is crucial for CCS projects and as an early starter this support will help accumulate technology understanding and experiences.

- ***Early Starter for Future Market:*** With a tight global target, CCS will be necessary to lead China to a low carbon future. The energy supply system world-wide will have a huge potential to employ CCS technology and create a new market for CCS. CCS will provide a huge business opportunity to Chinese enterprise if they become an early starter and can compete with their western counterparts.

Constraints

- ***No Global Consensus on long-term target:*** CCS is a solution to climate change but at a cost of lower energy efficiency. Thus the only incentive for countries to employ CCS technology is if they have an emission target and CCS can help them to achieve this target with feasible and acceptable cost. The largest challenge for CCS in the future is the lack of consensus on long-term targets. EU has argued that a two degree temperature increase could be a global target and Copenhagen Accord has confirmed the announcement from G8 that the scientific view agreed that global temperature increase should be no more than two degrees. However, the long term target has still not translated into a global budget and individual target for each country. Without such clear target, it will be difficult for countries to employ CCS technology at large scale.

- ***Not eligible for international carbon market:*** Under the current international climate regime, developed countries have quantified emission reduction target while developing countries like China may take voluntary mitigation actions with the support from developed countries. Due to its higher mitigation cost, developing countries have no incentive to employ CCS technology without international support in terms of finance and technology transfer from developed countries. CDM is a possible channel for

developing country to seek international support for CCS but due to political disagreement, CCS is still not eligible for CDM under the current framework. That means CERs from CCS project in developing countries is not eligible to be used to fulfill commitment of developed countries. Thus there will be no incentive for developed countries to purchase CERs from CCS projects resulting in a deadlock for large scale implementation of CCS project.

- ***Public concerns about leakage:*** The deployment of CCS on a large scale is associated with risks. These risks are mainly due to the fact that CCS involves storing millions of tonnes of CO_2 per year with the possibility that the injected gas may spread over a large area and the subsurface pressure could show effects at a large distance from the injection site. Regulatory frameworks that manage health, environmental, financial, and property risks and liabilities associated with CCS are considered by many to be required if CCS is to be adopted on a large scale. In order to gain public acceptance of CCS and achieve investors' commitment, these regulatory frameworks should be globally consistent and nationally coordinated.

- ***Technology breakthrough in other alternatives:*** CCS is one of the mitigation options beinjg considered but is not the only options. There are many alternative technologies which can also contribute to emission reduction on a large scale but may have a higher cost when greater reductions are made. One of the advantages of CCS technology is that it provides a "cap" for mitigation costs. However, if some competitive technology has a breakthrough and reduces its mitigation cost greatly, the investment in CCS could be lost. CCS technologies. There is also the concern that CCS technology could crowd out R&D funding for other technologies.

6.2 Analysis at the project level

From the SWOC analysis at project level, the following results based on three processes of CCS, including capture, storage and transport, are summarized as follows:

<u>**Carbon Capture System**</u>

Strengths

- ***High efficiency:*** IGCC is an advanced power generation technology, which can reach efficiency of 45% and potential to be at 50% or even higher to 55%- 60% in the future.

Combined with CCS, the demonstration project may have an efficiency penalty of around 9-11 %-points – depending on the degree of integration.

- ***Higher environment performance:*** IGCC is integrated with gasification technology which provides potential to treat the flue gases by mature and commercial technologies for pollutant reduction, resulting in low SOx, and NOx emissions and also the potential for reducing the water consumption.

- ***Flexible production:*** Gasification technology provides opportunity for multiple products including not only electricity and heat, but also fuels or materials such as methanol, DME, ammonia and FT diesel with integration of CCS technology. Several demonstration plants on coal to liquid fuel have been implemented by Shenhua group, which might be useful for the demonstration of IGCC with CCS.

- ***Promising options:*** The operational experience in the first stage of GreenGen will provide valuable information for the second and the third phases when CCS is considered and combined into future development. In addition to the experience with IGCC plants on a large scale, there is also experience available with carbon capture from syngases in the chemical industry.

Weaknesses

- ***Higher Investment Cost:*** Compared to conventional power generation technology, IGCC systems are complex, making it more difficult for the power industry to accept it; the technology is in its developmental stage, and currently, its cost is relative high.

- ***Higher Mitigation Cost:*** The high mitigation cost of CCS means only high carbon price make CCS economically attractive. The current CER price in China is only about 10 $/tCO2 and even a relatively high CO_2 price of $45/tonne only just makes CCS economic. When the likely impact of appraisal optimism is included, it is clear that a significantly higher price than this would probably be required. Recent industry estimates indicate that most of capital costs data that were used in previous cost estimations are too low. EOR revenues will make some difference but it is very unlikely to be enough without a strong additional incentive from the carbon market or another complementary form of revenue support.

- ***Optimised integration of polygeneration and CCS:*** The existing coal-based IGCC power plants built in Europe and also stage I of GreenGen were designed based on maximizing

overall net plant efficiency. For future plants, the concept will be based on a polygeneration plant with hydrogen production and CCS, as a consequence, plant concepts may be different between.

- ***Project management for "first time projects":*** As a first of the kind project for the project owner, the management for such a project will be a considerable risk for project construction and project management.

- ***Up-scaling of existing technology for large scale capture:*** For every new technology, one of the most important gaps is up-scaling from demonstration to full size commercialization. The up-scaling of existing capture, transport and storage technology to a large scale is a great challenge for the project owner.

- ***Monitoring, validation and verification practice:*** Accurate measurement and calculation of stored carbon dioxide is crucial to the success of this demonstration project for two reasons. The first one the accurate estimation of stored carbon dioxide which is important when the reduced emissions become a tradable certification. Monitoring, validation and verification equipment and guidelines are also important challenges for the demonstration project for its success.

Carbon Dioxide Storage

There are three oilfields around Tianjin IGCC power plant: Huabei, Dagang and Shengli oilfield complexes, which can be considered as potential storage sites (Fig. 9).

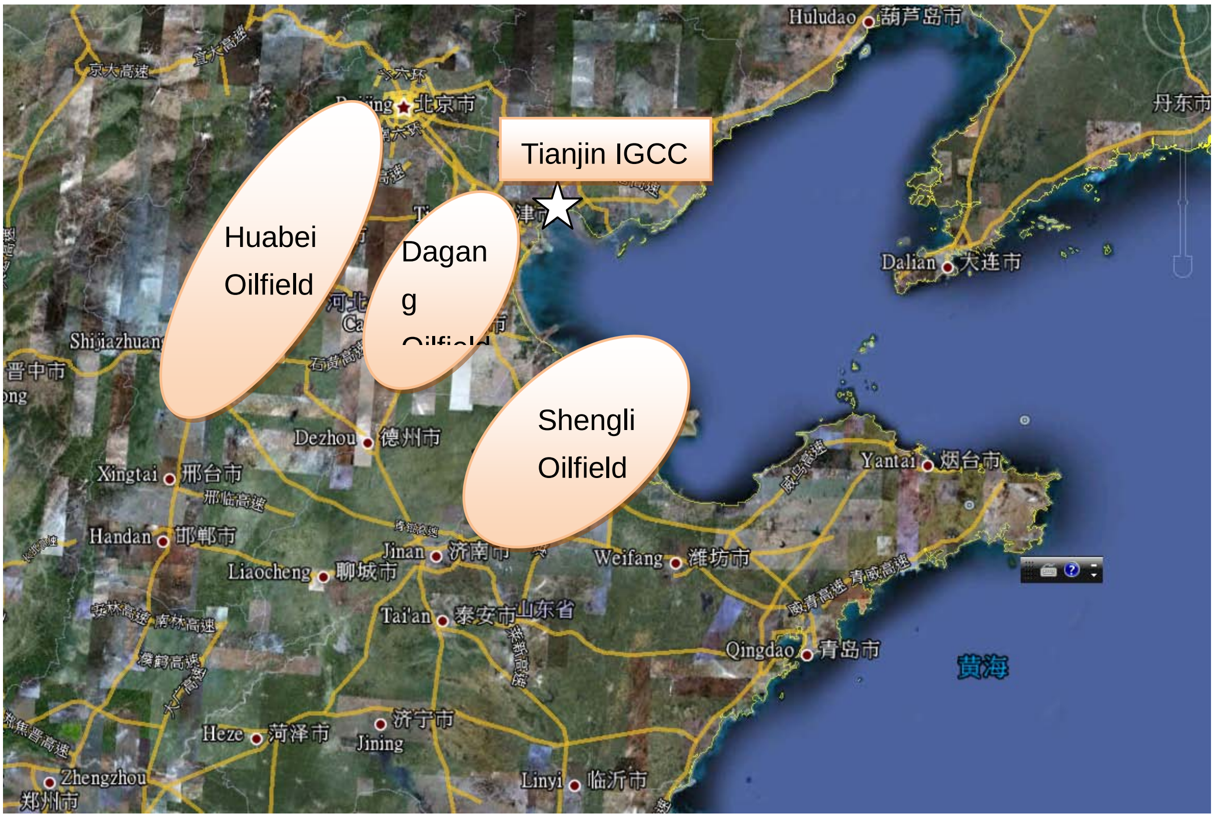


Figure 9 The three main oilfields in the vicinity of Tianjin

The strengths and weakness of the three oilfields are shown in Table 8.

Table 8 Strengths and Weakness of Three Oilfields Near to GreenGen IGCC Plants

Oilfield	Strengths	Weakness	Suitable applications
Dagang	Close to GreenGen project (only 50 km), existing infrastructure for gas and oil transportation	Relatively smaller capacity, not suitable for large scale storage	Suitable for small scale pilot project, EOR potential for storage.
Shengli	Larger storage capacity (460 $MtCO_2$), existing infrastructure for gas and oil transportation,	Longer distance for transportation	suitable for large scale pilot project (about 230 years), EOR potential for storage.
Huimin sub-basin	Much larger storage capacity (0.7 $GtCO_2$), existing infrastructure for gas and oil transportation.	Longer distance for transportation, higher uncertainty in capacity estimation, lack of information for deep saline formation, no economic incentive for storage.	suitable for large scale pilot project.

Carbon Dioxide Transport

In the COACH project, three transportation options were investigated including pipeline, ship and railway. According to the COACH study, transporting CO_2 by pipeline could be economically feasible when the pressure is greater than 8.6 MPa and less than 15.3 MPa. Large-scale transport of CO_2 by ship could also be done in semi-pressurized tankers.

For the Shengli oilfield complex, the three transportation options are all applicable. However, for Huimin sub basin and Dagang oilfield complex, transportation through pipeline is the only option. A case study of transporting 4000 tonnes of CO_2 per day to a distance of 300 km shows the average transport cost is around 43 RMB/t for pipeline and 44 RMB/t for ship and 77 RMB/ton for railway, respectively. Thus railway is not preferred due to cost consideration while pipeline and ship are almost similar in terms of unit transportation cost.

Following gaps have been identified for the implementation of IGCC-CCS project:

Technological gaps

For implementing an IGCC-CCS demonstration project in China, the main technology gap exists in the storage section. In the case of saline aquifer storage, the difficulties often lie in site characterization (due to lack of pre-existing data), hydro-geological modeling and verification, risk detection and management, the experience gained in baseline measurement planning, etc. For the very first demonstration project, international cooperation is a practical method of filling these gaps.

Technical gaps may also lie in CO_2 pipe transport. China does not have experiences in large scale and long distance CO_2 transport. However, China does have strong capabilities in oil and natural gas pipelines, and remaining gaps can be filled by resorting to experiences of CO_2 pipe transport in EOR industry in US and other countries, or through China's own demonstration.

Since IGCC is new in China, high reliability and availability of operation of IGCC plant might need time for the demonstration, development and modification of technology.

Institutional gaps

CCS, as a new technology with cross-sectors requirements, resulting in a lack of clarity in where the responsibility for which government authority should be responsible for coordination and approval of the project. This calls for an urgent intuitional arrangement and guideline for the project's approval. Extension of the regulation based on existing power generation, coal-based chemical industry, EOR for oil industry with additional considerations of requirements for CCS might be one approach for the regulation establishment.

Attention shall also be paid for the phase of site closure and post closure management. No experience on this aspect has been referred to.

Legal and regulatory gaps

A set of regulation specifically related with CO_2 capture, transport and storage should be established almost from scratch. Among the required regulations are capture solvent emission standards in the capture plant, impurity specification in the transportation-ready CO_2 stream, regulations for the right-of-way of CO_2 pipelines, standards for monitoring and inspection of CO_2 pipelines, etc.

Financial gaps

By implementing CCS, the IGCC plant will face higher costs associated with the capture facility construction, operation, and energy penalty. This is not only a capital cost to the plant but an increase in electricity production costs. This reduces plant profitability and incentive for financiers to invest in the project. Government funding is likely to be necessary to help industry overcome this gap.

Some technical risks associated with CCS are also a gap that needs to be overcome for attracting investments for a CCS project. Uncertainty in regulation for the long term management of storage site is another one of the financing gaps.

7. CRITERIA AND AHP ANALYSIS FOR SITE SELECTION AND FOR THE DEMONSTRATIONS IN CAPTURE TECHNOLOGIES AND STORAGES

7.1 IGCC GreenGen Project

The proposed GreenGen IGCC+CCS demonstration project is located in the Linghai Industry District of Tianjin City by the Bohai Bay. The project is 40km east of Tianjin downtown, 10km from Tanggu District of Tianjin and 2km from the Tianjin Harbour (Fig. 10). The power generated from the project will be connected to Tianjin Power Grid of North China Power Grid (Fig. 11).

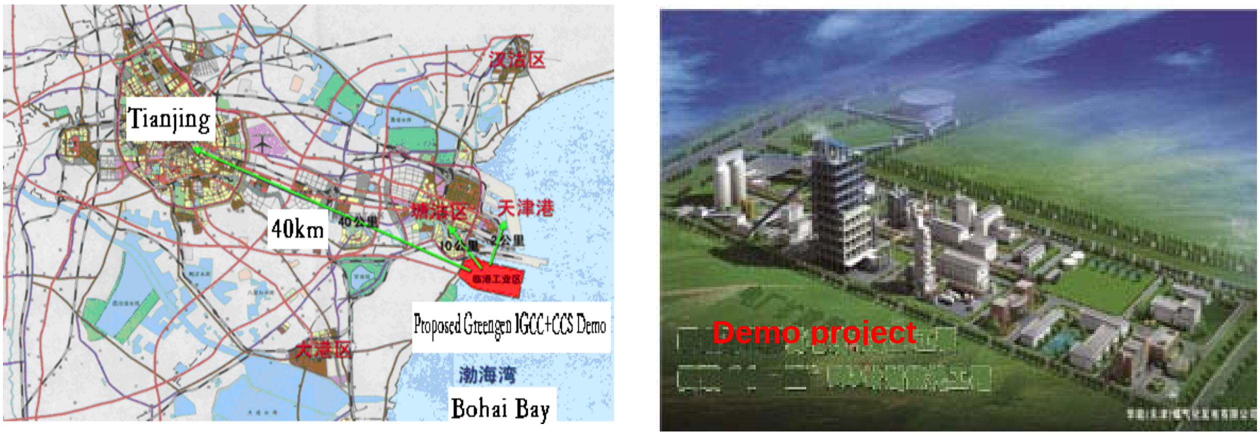


Figure 10 Geographic location of the proposed CCS demo project[8]

[8] Information provided by GreenGen Company

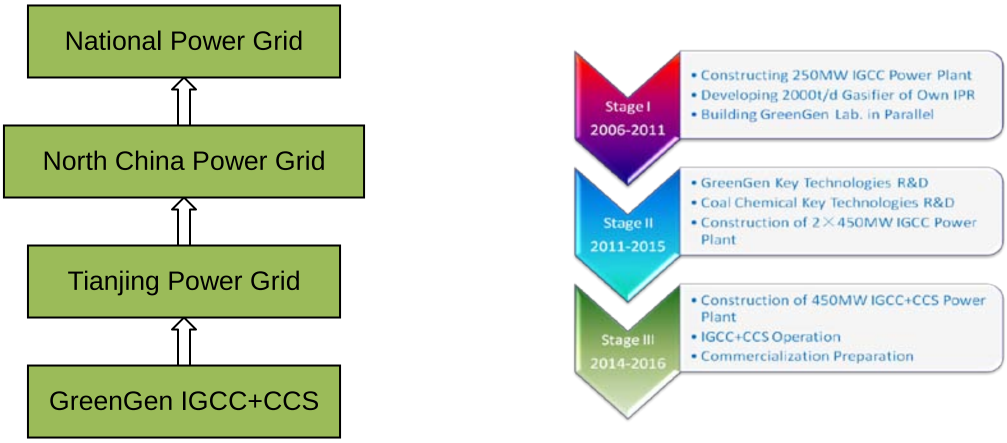


Figure 11 GreenGen CCS demo project in the National Power Grid and Three Stages of the Implementation

The project will be implemented in three stages (Fig. 11). The first stage includes the construction of a 250 MW IGCC power plant and a GreenGen laboratory from 2006 to 2011. The second stage will cover the key technology R&D and the construction of 2 X 450MW IGCC power plant. The third stage, from 2014 to 2016, is the construction and commercial operation of the 450 MW IGCC+CCS GreenGen near-zero emissions demonstration project. The project will develop large-scale hydrogen production based on coal, in which hydrogen gas turbine power generation and other CCS technologies will be verified.

7.2 Site Candidates

Site selection of IGCC plant with CCS is a complex process. Many factors shall be considered, for example, oil fields or coal fields, fuel supply, electricity load, water resources, and logistic infrastructure etc. In order to investigate the impacts by the above factors, two virtual IGCC+CCS plants have been assumed. Based on the communication with GreenGen, alternative candidates for the IGCC+CCS include Tianjin (based on Tianjin IGCC stage II) and Yulin IGCC+CCS in Shaanxi Province as shown geographically in Fig. 12.

Figure 12 Location of alternative storage sites

It shall be pointed out that Yulin IGCC+CCS is included for the comparison with Tianjin IGCC+CCS for the comparison of the two candidates to test the method although detailed analysis of the plant needs to be further investigated.

7.3 Criteria for Site Selection

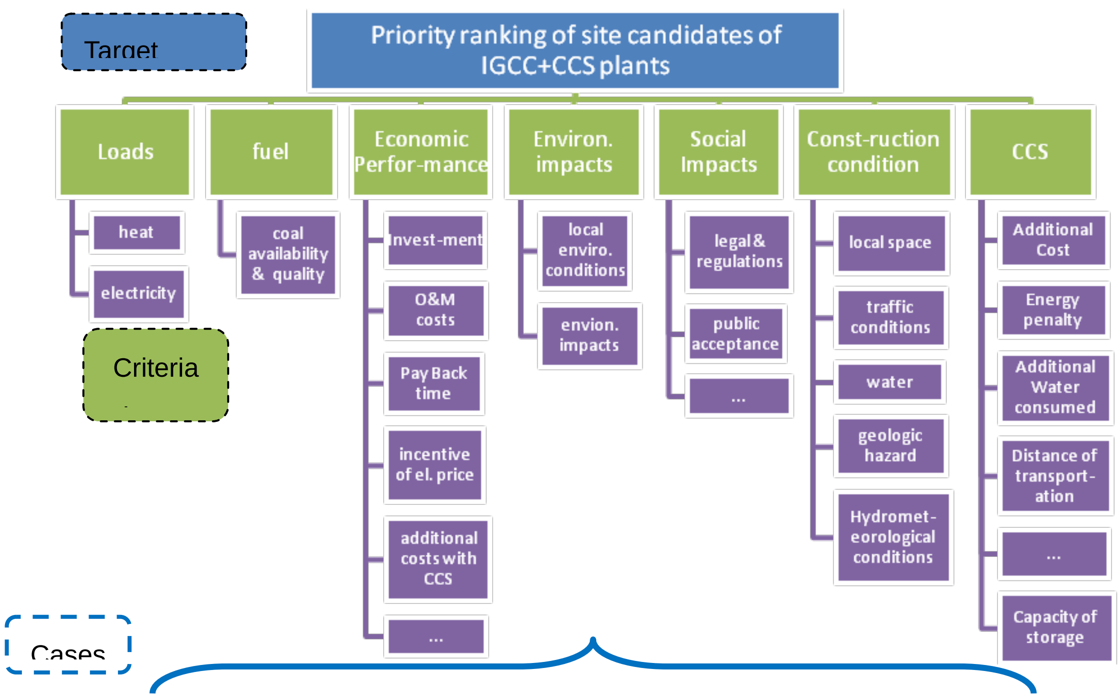
In order to select the plant site with multiple considerations of the complex of various factors, the so called AHP (Analytic Hierarchy Process), a structured technique for dealing with complex decisions, is applied for the site selection and comparison. Table 9 lists criteria for the site selection of different coal based power plants including super-critical power plants, IGCC and IGCC+CCS plants.

Table 9 Criteria for site selection for different type of power plants

Criteria for selecting site	regular super critical power plant	IGCC power plant without CO_2 capture	IGCC+CCS power plant
Load	Heat Load	Heat Load	Heat Load
	Electricity Load	Electricity Load	Electricity Load
Economic performance	Investment Cost	Investment Cost	Investment Cost
	O&M Cost	O&M Cost	O&M Cost
	Payback time(PBT)	Payback time(PBT)	Payback time(PBT)

	-	Subsidy of electricity price	Subsidy of electricity price
		Incentive of el. price	Incentive of el. price
		-	Additional Cost
CO2 Capture	-	-	Energy penalty
			Additional Water consumed
CCS	-	-	Distance of transportation
			Cost of transportation
			Safety of transportation
			Capacity of storage
			Geological conditions of storage site
			Risk of storage
			Cost of storage
Fuel	Fuel Conditions (Availability, Quality)	Fuel Conditions (Availability, Quality)	Fuel Conditions (Availability, Quality)
Environmental Impact	Local environment conditions	Local environment conditions	Local environment conditions
	Environmental Impacts	Environmental Impacts	Environmental Impacts
Construction condition	Traffic conditions	Traffic conditions	Traffic conditions
	Local Space	Local Space	Local Space
	Construction conditions	Construction conditions	Construction conditions
	Geologic hazard	Geologic hazard	Geologic hazard
	Hydrometeorological conditions	Hydrometeorological conditions	Hydrometeorological conditions
	Water source	Water source	Water source
Social impacts	Legal and regulations	Legal and regulations	Legal and regulations
	-	Public acceptance	Support from local government

The above criteria have been considered based on hierarchical structure as shown in Fig. 13.



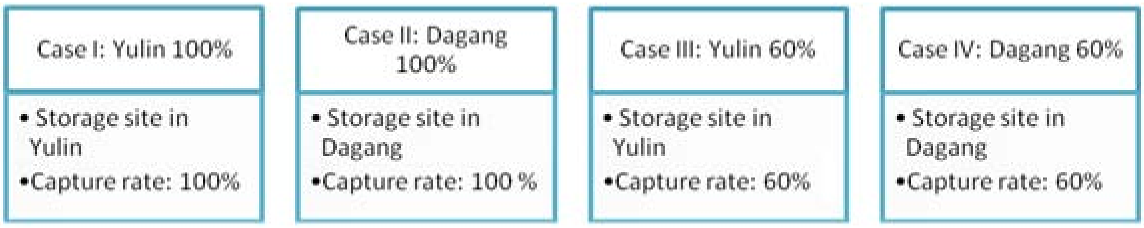


Figure 13 Hierarchical model for the site selection of IGCC+CCS demonstration

7.4 Results

Based on the criteria (Table 9) and their relationship (Fig. 13), the site candidates (cases) can be assessed by an AHP method. Through consultation by questionnaire delivered in the inception workshop and discussions among IA, EA, and the consultant team, weighting were given to the criteria (value 1 to 9) . Four cases were defined based on the combination of two different storage locations of Dagang and Yulin with 60% or 100% capture rate. Based on each criterion, performance of four cases is compared to determine the values for the overall assessments using AHP.

By using AHP, the four cases have been analyzed from the perspective of different stakeholders, for example, government or industry, as shown in Table 10. Different stakeholders have different views for the site selection of IGCC+CCS due to the different expected targets. For government, the major goal is to demonstrate the feasibility and long term development of new technologies, such as IGCC with CCS. However, for industry, the focus is on the economic benefits while developing new technologies for their future market competiveness. The case of Yulin with capture rate of 60% have highest ranking compared to other cases from the viewpoints of both government and industry. The lowest ranking is the case, Yulin with 100% capture rate. It should be noted that the storage sites were considered based on location and not geological criteria for the purposes of this study.

Table 10 Site ranking by AHP analysis

Case	Stakeholder: Government	Stakeholder: Industry
Yulin100%	★☆☆☆☆	★★☆☆☆
Dagang 100%	★★☆☆☆	★☆☆☆☆
Yulin 60%	★★★★★	★★★★★

Dagang 60%	★★★☆☆	★★★★☆

7.5 Sensitivity Analysis

To investigate the uncertainty of the decision making process by AHP, a sensitivity analysis was conducted with considerations of different electricity prices, coal prices, and distance of CO2 transportation as shown in Tables 11-13.

Table 11 Sensitivity of site ranking vs. electricity price

Stakeholder	Government			Industry		
Electricity price (¥/MWh)	550	800	1200	550	800	1200
Yulin 100%	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★★☆☆☆	★★☆☆☆	★☆☆☆☆
Dagang 100%	★★☆☆☆	★★☆☆☆	★★☆☆☆	★☆☆☆☆	★☆☆☆☆	★★☆☆☆
Yulin 60%	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★	★★★★☆
Dagang 60%	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★★☆	★★★★☆

Table 12 Sensitivity of site ranking vs. CO2 transportation distance

Stakeholder	Government			Industry		
Distance (km)	50	80	200	50	80	200
Yulin 100%	★★☆☆☆	★☆☆☆☆	★☆☆☆☆	★★☆☆☆	★★☆☆☆	★☆☆☆☆
Dagang 100%	★☆☆☆☆	★★☆☆☆	★★☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆
Yulin 60%	★★★★★	★★★★★	★★★★☆	★★★★★	★★★★★	★★★★☆
Dagang 60%	★★★☆☆	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	★★★★★

Table 13 Sensitivity of site ranking vs. coal price

Stakeholder	Government			Industry		
Coal price (¥/t)	325	425	525	325	425	525
Yulin 100%	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★★☆☆☆	★★☆☆☆	★☆☆☆☆
Dagang 100%	★★☆☆☆	★★☆☆☆	★★☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆
Yulin 60%	★★★★	★★★★	★★★★★	★★★★	★★★★	★★★★

	★	★		★	★	☆
Dagang 60%	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★★☆	★★★★☆

The sensitivity analysis showed that when the electricity price, coal price or transportation distances became high, the ranking of the Yulin cases decreased. This is due to the removal of Yulin's advantages which are the low price of coal and high electricity price. Studies in this project on the site selection suggest the following observations:

- Case III: Yulin with 60% capture rate gained the highest ranking from the viewpoints of both governmental and industrial stakeholders.
- For government stakeholders, electricity price has little impact on the final decision of plant site. However, for the industrial stakeholders, Yulin cases became more attractive when electricity price increases.
- When the transportation distance is less than 200 miles, the Yulin case with 60% capture is more attractive than Dagang case with 60% capture, which indicates that the case Dagang has an advantage in long distance transportation, due to the increase of CO2 transportation cost in Yulin 60%, when the transportation distance increases.

Based on the results, the following recommendations for the site selection of IGCC+CCS power plant are made:

- When considering the importance and uncertainty of the storage site in the whole chain of CCS, the feasibility and suitability of the storage need to be considered early in the CCS project.
- The economic performance of a demonstration plant is the key factor determining the competitiveness of IGCC+CCS technology. The low costs in fuels and land use need to be selected for better economic performance. This implies that west area of China may be more preferable for first IGCC+CCS demonstration plant where land costs are lower and feedstock transportation costs are lower.
- Subsidies or incentive with favorable electricity prices, tax relief, and clear regulations are of extreme importance for the demonstration and implementation of CCS projects in China. This suggests that a rapid action from governments is needed to establish long term policies on CCS.

8. CO_2 STORAGE CAPACITY IN RESERVOIRS AND SALINE AQUIFERS IN DAGANG OILFIELD FOR GREENGEN CCS DEMONSTRATION PROJECT

8.1 Methodology for the estimation of CO_2 storage capacity

Estimation of CO_2 storage capacity, the volume of pore space available in a given rock formation, for hydrocarbon fields and aquifers is conducted based on the methodology by The Carbon Sequestration Leadership Forum (CSLF) as shown in Fig. 14[9]. Storage capacity on coal mines is based on the assumption that CO_2 will displace coalbed methane. It shall be pointed out that the estimation is preliminary as many factors have been either simplified or ignored e.g. water influx, gravity segregation, reservoir heterogeneity, reservoir permeability and fluid viscosity.

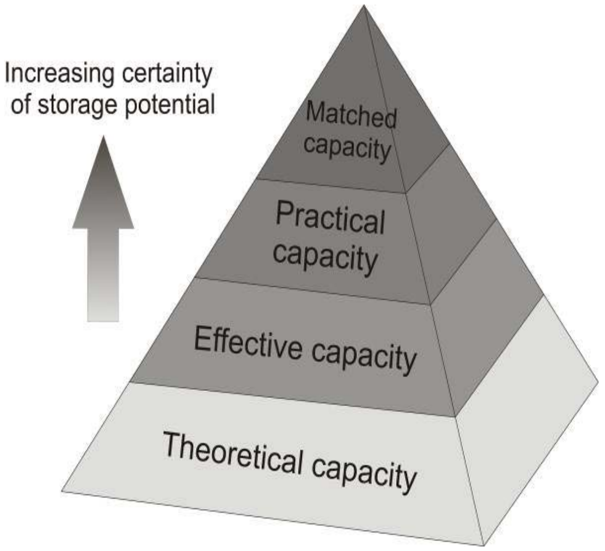


Figure 14 The CSLF techno-economic resource – reserve pyramid for geological storage

[9] Bachu,S.et al, 2007 Phase II Final Report from the Task Force for Review and Identification of Standards for CO_2 Storage Capacity Estimation: Estimation of CO_2 storage capacity in geological media – phase 2.

The storage capacity is described as theoretical (assumes all pore space can be utilized), effective (considers geological limitations), practical (economic factors considered) or matched (source–sink match). The practical and matched CO_2 storage capacities have to be evaluated on a case–by–case basis considering economic factors, location of CO_2 sources, regulatory requirements, and numerical and economic modeling, bearing in mind that CO_2 storage and CBM production require a high well density and it is uneconomic to develop the necessary infrastructure for areas with low storage capacity.

8.2 Criteria for the assessment of CO_2 geological storage

Assessment criteria for carbon dioxide storage site are established according to the properties of the geological storage, including depth, fault sealing, exploration degree, rock properties and sealing, as shown in Table 14.

Table 14 Criteria of geological storage

Evaluation	Ideal	Favorable	Acceptable	Unfavorable	Bad
Depth(m)	>2000	>1500	1000	500	<500
Fault Sealing	Better	Good	ordinary	Bad	Worse
Exploration Degree	1.0–0.75	0.75–0.5	0.5–0.25	0.25–0.1	0.1–0
Rock Properties	Clastic Rocks Layered Distribution	Complex Layered Distribution	Carbonate Layered Distribution	Non–layered Distribution	No Salt Rock
Sealing Hg (m)	>400	200–400	100–200	0–100	≤0

With reference to the miscible and immiscible flooding characteristics of Chinese hydrocarbon reservoirs and the quantified data, the criteria for CO_2 EOR storage are shown in Table 15 and Table 16, respectively.

Table 15 Miscible CO_2 EOR storage criteria

Evaluation	Ideal	Favorable	Acceptable	Unfavorable	Bad
Permeability (mD)	0.1–10	10–50	50–200	200–500	>500
Viscosity (mPa.s)	<2	2–4	4–8	8–10	>10
Porosity (%)	10–15	15–20 8–10	20–25 6–8	25–30 4–6	>30 <4
Depth (m)	1500–2000	2000–2500 1200–1500	2500–3000 1000–1200	3000–3500 800–1000	>3500 <800
Temperature (℃)	80–90	90–100 70–80	100–110 60–70	110–120 50–60	>120 <50
Density (g/cm3)	<0.82	0.82–0.86	0.86–0.88	0.88–0.90	>0.9
Formation Dip (°)	>70	50–70	30–50	10–30	<10
Reservoir Thickness (m)	<10	10–20	20–30	30–40	>40
Reservoir Pressure (MPa)	15–20	20–25	25–30	30–35	>35
		12–15	10–12	8–10	<8
Oil–wet Index	0.8–1	0.6–0.8	0.4–0.6	0.4–0.2	0–0.2
Oil Saturation (%)	>70	55–70	40–55	25–40	<25
Hg (m)	>400	200–400	100–200	0–100	≤0

Table 16 Immiscible CO_2 EOR storage criteria

Property	Value
Viscosity (mPa.s)	100–1000
Density(g/cm3)	>0.9
Oil Saturation(%)	30–70
Depth (m)	600–900
Reservoir Thickness (m)	10–20
Permeability Variation Coefficient	0.5–0.55

8.3 Estimation of CO_2 storage capacity in oil and gas reservoirs

The CSLF equations for oil and gas fields assume that reserves can be replaced by CO_2:

For gas fields:

$$M_{CO_2tg} = OGIP_s \times R_f \times \rho_{CO_2} \times (1 - F_{IG}) \times \left(\frac{(Ps \times Z_r \times T_y)}{(P_r \times Z_s \times T_s)} \right) \quad (1)$$

For oil fields:

$$M_{CO_2to} = \rho_{CO_2} \times \left(\frac{(R_f \times OOIP)}{(B_o - V_{iw} - V_{pw})} \right) \quad (2)$$

An alternative version for oil and gas fields is based on the geometric size of the reservoir:

$$M_{CO_2th} = \rho_{CO_2} \times (R_f \times A \times h \times \varphi \times (1 - S_w) - V_{iw} + V_{pw}) \quad (3)$$

The effective version of this calculation assumes that most the recoverable reserves of the oil can be largely replaced with CO_2. This is generally valid for pressure–depleted reservoirs that are not subject to water drive from surrounding aquifers, or where water–flooding has not been applied. Where water has invaded the reservoir, it is assumed that CO_2 can displace some but not all of this fluid, and so the estimated storage capacity is reduced. Storage capacity is also affected by the difference in density between oil and CO_2 (leads to gravity segregation), CO_2 mobility with respect to water and reservoir heterogeneity[10,11]

[10] Bondor 1992, Applications of carbon dioxide in enhanced oil recovery, Energy Conversion and Management, Vol. 33, 579–586.

[11] Doughty and Preuss 2004, Modeling supercritical carbon dioxide injection in heterogeneous porous media. *Vadose Zone Journal,* Vol. 3, no. 3, p. 837-847.

The effective storage capacity is calculated as

$$M_{CO_2eh} = M_{CO2t} \times \left(C_m \times C_b \times C_h \times C_w \times C_a\right) \quad (4)$$

The formula used for the COACH and NZEC projects, including a discount to allow for irreversible water invasion is based on the above calculations. The storage coefficient was based on the reports of Vangkilde–Pederson[12] for the value of the storage coefficient where insufficient data are available (based on computer models):

$$M_{CO_2eh} = URR_s \times B_o \times \rho CO_2 \times S_{coeff} \quad (5)$$

The practical storage capacity requires the effective storage capacity value and takes into account economic factors. For example, many reservoirs have a small storage capacity, rendering them uneconomic. Building the infrastructure is costly, so larger storage sites are preferred. Matched capacity is identified when sources and matched to storage sites (sinks).

Where, M_{CO2t} = estimated theoretical estimated storage capacity (M_{CO2tg} for gasfields, M_{CO2to} for oilfields and M_{CO2th} for hydrocarbon fields) (kg); M_{CO2eh} = estimated effective storage capacity of hydrocarbon fields (kg); $OOIP_s$ = Original Oil In Place – volume of oil at standard temperature and pressure (Mt can be converted to m^3 using API value of oil); URR = Ultimately Recoverable Reserves (m^3); R_f = recovery factor; F_{IG} = fraction of injected gas; P = pressure (P_r at reservoir conditions, P_s at standard conditions) (Pa); T = temperature (T_r at reservoir conditions, T_s at standard conditions) (ºC); Z = gas compressibility factor (Z_r at reservoir conditions, Z_s at standard conditions); B_o = Formation volume factor; ρ_{CO2} = Density of CO_2 in the reservoir (kg/m^3); V_{iw} = volume of injected water (m^3); V_{pw} = volume of produced water (m^3); A = reservoir area (m^2); h = reservoir thickness (m); Φ = porosity (fraction); S_w = water saturation (fraction); C_m = mobility coefficient; C_b = buoyancy coefficient; C_h = heterogeneity coefficient; C_w = water saturation coefficient; C_a = aquifer strength coefficient; S_{coeff} = storage coefficient to discount for water invasion etc (fraction).

The CSLF methodologies do not calculate CO_2 storage during CO_2–EOR. However, Bachu et al (2007) note that the storage capacity obtained during computer simulations is considered an effective estimate. Initial screening of reservoir sites for EOR is usually based on reservoir depth, temperature and pressure, minimum miscibility pressure (MMP) and oil gravity[13, 14, 15]

---

[12] Vangkilde–Pederson et al., 2008, Storage Capacity Standards. EU GeoCapacity Deliverable D24, 39

[13] Taber et al 1997, EOR screening criteria revisited – part 1: introduction to screening criteria and enhanced recovery field projects. SPE Reservoir Engineering, Vol. 12(3), 189–198.

[14] Kovscek 2002, Screening criteria for CO_2 storage in oil reservoirs. Petroleum Science and Technology, Vol. 20(7-8), 841-866.

and that this selection is narrowed to CSLF “practical capacity” based on the recoverable reserves.

8.4 Estimation of CO_2 storage capacity in aquifers

Aquifer storage is based on displacement of native pore fluid. For significant storage to be possible, it is necessary for a significant proportion of the native pore fluid to be displaced from the aquifer over the injection period. This may be occur either by production of formation water (additional wells required) and/or by migration of groundwater into adjacent formations and/or to the ground surface or seabed. Overall storage capacity is the amount of CO_2 that will be eventually trapped by filling structural and stratigraphic traps plus CO_2 trapped on the migration pathway or dissolved into the pore fluids. Mineral precipitation is considered a slow process and so not considered over injection timescales. The calculation of storage capacity for aquifers mainly depends on the estimated volume for the aquifer which lies within closed traps. The theoretical CSLF calculation assumes all the pore space can be filled.

$$M_{CO_2ta} = A \times h \times \varphi \times \rho_{CO2} \times (1 - S_{wirr}) \tag{6}$$

The effective capacity considers the volume of closed traps, trap heterogeneity, irreducible water saturation and buoyancy coefficient. For NZEC, these capacity limiting factors were amalgamated into a single storage coefficient (as for the GeoCapacity and COACH projects[16,17]). The CSLF based methodology (Bachu et al., 2007) for storage capacity in aquifers is calculated using the following formula:

$$M_{CO_2ea} = A \times h \times \varphi \times \rho_{CO2} \times (1 - S_{wirr}) \times C_c \tag{7}$$

For the COACH and NZEC projects, this was simply written as:

$$M_{CO_2ea} = A \times h \times \Phi \times \rho_{CO2} \times S_{coeff} \tag{8}$$

---

[15] Shaw and Bachu 2002. Screening, evaluation, and ranking of oil reservoirs suitable for CO_2-flood EOR and carbon dioxide sequestration. Journal of Canadian Petroleum Technology, Vol. 41(9), 51–61.

[16] Zeng, R.,et al., 2009. Cooperation Action Within CCS China-EU D3.1. Assessment of CO_2 storage potential of the Dagang and Shengli oilfield provinces, Jiyang depression and Kailuan mining area.

[17] Vincent, C., 2010 (in press). Evaluation of carbon dioxide storage potential for the Bohai Basin, north-east China. *International Journal of Greenhouse Gas Control*

Where S_{coeff} is an estimated storage coefficient, this was taken from Vangkilde–Pedersen et al., 2008 for regional scale calculations. Where, M_{CO2ta} = estimated theoretical aquifer storage capacity (kg); M_{CO2ea} = estimated storage capacity (kg); A = area of the aquifer (m^2); h = average height of the aquifer × net:gross ratio (m); ρ_{CO2} = Density of CO_2 in the aquifer (kg/m^3); Φ = average porosity of the aquifer (fraction); S_{wirr} = irreducible water saturation; C_c = storage coefficient that incorporates aquifer heterogeneity, CO_2 buoyancy and sweep efficiency; S_{coeff} = storage coefficient that incorporates irreducible water saturation, aquifer heterogeneity, CO_2 buoyancy and sweep efficiency.

8.5 Preliminary assessment of CO2 storage in reservoir and saline aquifer

Description of geology and reservoir

Dagang oilfield complex is located in Cang county, Hebei province at a distance of around 60 km to Tianjin. Exploration began in 1964, and the field was developed in 1968. In total, 16 oilfields were developed; total oil- bearing area is 640 km^2 and total geologic reserve nearly 1.1 billion tons of oil (Fig. 15).

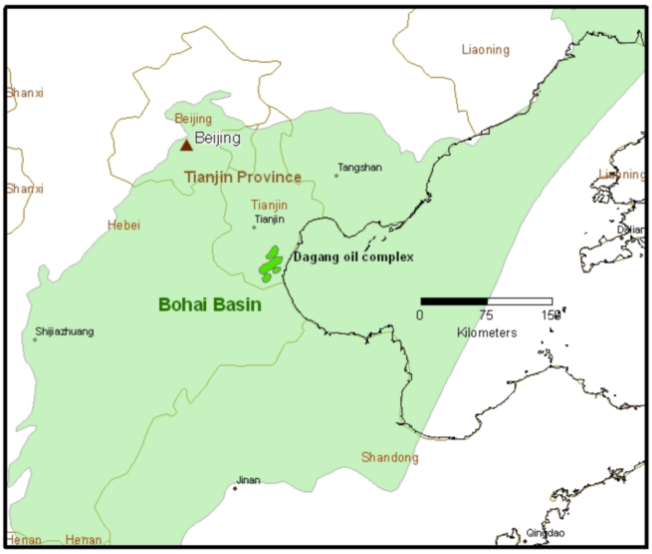


Figure 15 Geographic location of Dagang oilfield complex

Dagang oil field is in Huanghua depression, a secondary unit of Bohaiwan Basin. Bohaiwan Basin is a rift-subsidence basin, frequent tectonic movements during the Cenozoic divided the basin into many fault blocks. Structure in Huanghua depression is very complex and the Dagang oilfiled is structurally complex.

Main oil reservoir rocks in the Dagang field are of Tertiary age. These reservoir formations include the Dongying Group, Guantao Group and Minghuazhen Group. All these formations

are fluvial facies, Fluvial environment of depositon contributes to the complexity of the Dagang oilfield. Reservoir type considered to have best potential for CO_2 storage: Complex block reservoir: bottom water reservoir or low permeability reservoir. Reservoir parameters of Gangdong oilfield are as follows:

- Reservoir type : Complex block reservoir
- Produce method : Water injection
- Wells : More than 700
- Rock type: sandstone
- Deposit : fluvial facies (meandering stream, braided stream)
- Production Layer: 50m thick sand layer group, made up of more 100 sand layer
- Single sand layer thickness: 2-10 m (most 3-5m)
- Average net pay:14.7 m
- Porosity: 31%
- Permeability:1000 mD
- Well space: 150 - 200m
- Geologic reserve: 79 million tones oil

Calculation of CO_2 utilization factor

The oil recovery factor K can be obtained:

$$K = \frac{\rho_{CO_2}\left[(1-S_w)E_R + C_{os}(1-S_w)(1-E_R) + C_{ws}S_w\right]}{\rho_o E_R (1-S_w)} \qquad (9)$$

Maximum effective storage capacity can be express as follows:

$$M_{CO_2-EOR} = KE_R(OOIP) \qquad (10)$$

Where, E_R is the recovery factor, V_{iw} and V_{pw} are ignored the volumes of injected and produced water, respectively, S_w is water saturation. ρand ρ_{CO2} is oil and CO_2 density at reservoir conditions, C_{ws} is dissolution factor of CO_2 in water, f; C_{os} is dissolution factor of CO_2 in crude oil.

CO_2 EOR storage potential in Dagang Oilfield Complex

According to the results and dates published, there are six sites suitable for CO_2-EOR (Table 17). The six sites of Dagang oilfield complex are showed in Fig. 16. The site E divided into two blocks, one for CO2 miscible flooding and another one for CO2immiscible flooding.

Table 17 Increased oil recoverable reserves during CO_2-EOR

Site	Increased oil recoverable reserves (Mt)		EOR rate (%)	
	Miscible flooding	Immiscible flooding	Miscible flooding	Immiscible flooding
A	0.18		7.95	
B	0.48		14.39	
C		0.40		7.64
D		***1.7***		***15***
E	***1.91***	***0.69***	***19.6***	***9.61***

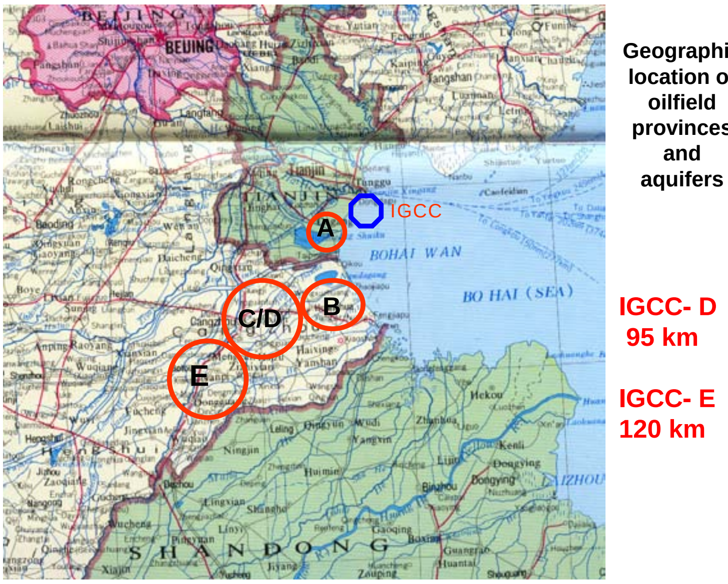


Figure 16 The six sites of Dagang oilfield complex

Based on the CO_2 utilization factor *K*, the storage capacity of CO_2-EOR can be obtained (Table 18).

Table 18 CO_2 storage capacity during CO_2-EOR

Storage site	Increased oil recoverable reserves (Mt)	CO_2 storage capacity (Mt)
A	0.18	0.90
B	0.48	3.05
C	0.40	2.61
D	**1.7**	**12.00**
E	**2.6**	**13.49**

The CO_2 storage capacity of sites D and E is over 25 Million tons.

Two sites of CO2- EOR storage in Dagang Oilfield Complex

<u>Site D</u>

Site D is an anticline structure. It consists of several sub-structures. They were controlled by main fault and formed independent oil-bearing traps respectively as shown in Fig. 17.

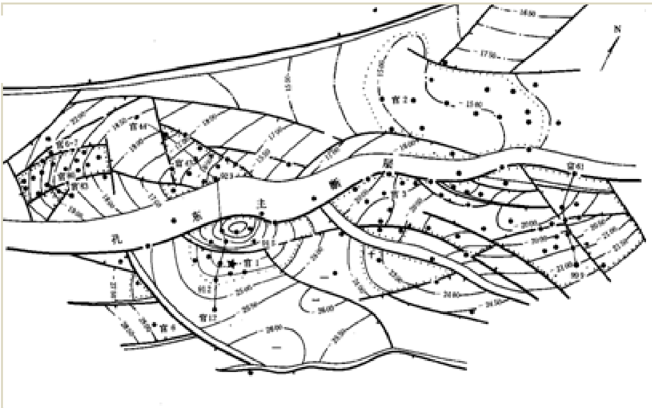


Figure 17 Geological structure in site D

Guan 3 section in Shahejie Group is a typical block in site D. It is a reverse drag anticline reservoir. Its height of structural closure is 125m, the thickness of gas-bearing reservoir is 26m and that of oil-bearing is 53m. The depth of boundary between gas and oil reservoirs is -1735m and that of boundary between oil and water is -1810 m as shown in Fig. 18.

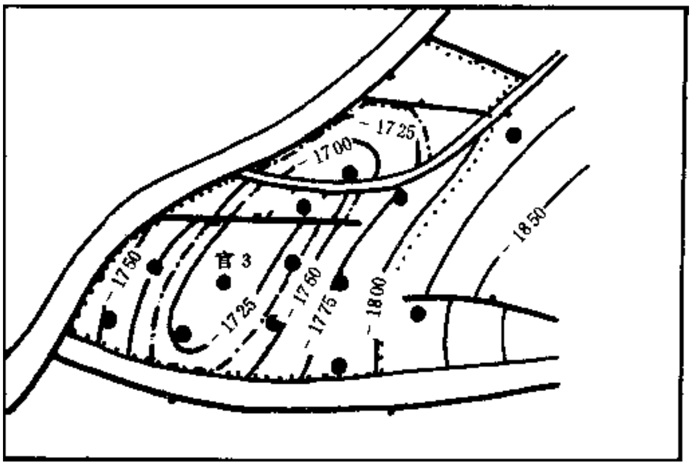


Figure 18 Guan 3 block in Shahejie Group in site D

The reservoir-sealing caprock pair is well developed. Especially there is a thick evaporite (more than 100m generally) over the reservoirs as shown in Fig. 19.

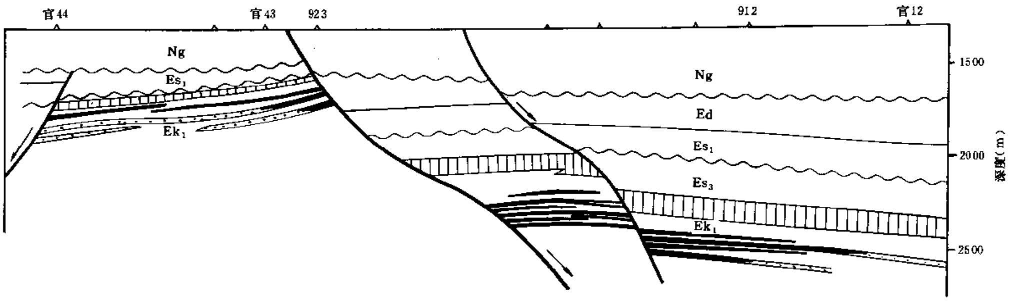


Figure 19 Caprock and reservoir pair in site D

Site E

Site E was controlled by fault along northeast trend (Fig. 20). Its area is 25 km^2. There were 26 normal faults developed. Distribution of oil-bearing reservoirs was stable, they had good connectivity. The effective thickness of reservoir in single well was more than 40m in general.

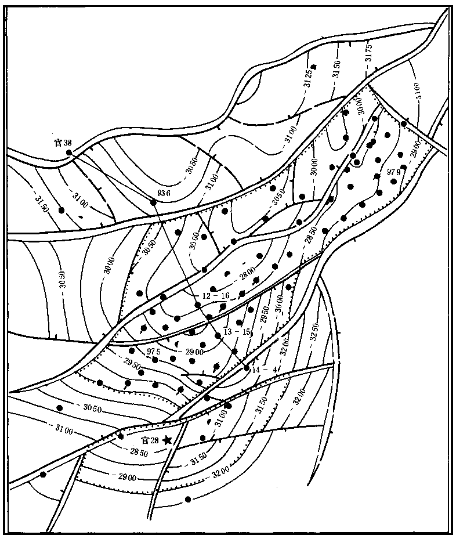


Figure 20 Geological structure in site E

The reservoir-sealing caprock pair is well developed also in Site E. There is a thick evaporite (more than 200 m) over the reservoirs (Fig. 21).

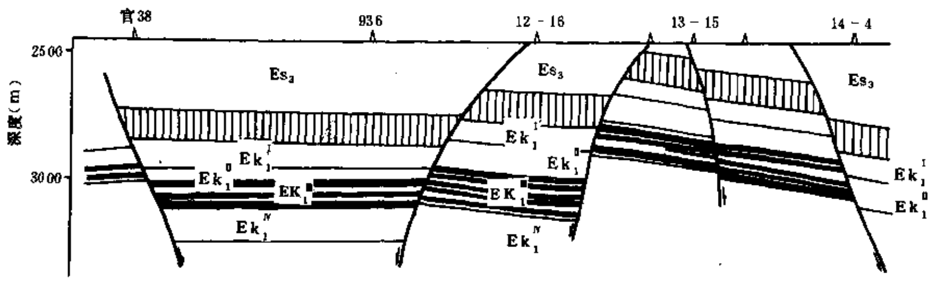


Figure 21 Caprock and reservoir in site E

8.6 CO_2 Storage in Saline aquifer

The CO_2 storage capacity in saline aquifer in Sites D and E is given in Table 19. The total amount of CO_2 is estimated from 38 to 55 Mt based on irreducible water saturation between 10 to 40 %.

Table 19 CO_2 Storage Capacity in saline aquifer in Sites D and E

Storage Blocks	Area Km^2	Sirr	Totalamount (Mt)	Sirr	Total amount (Mt)
A	50	0.1	29.33	0.4	20.40
B	45	0.1	10.06	0.4	7.00

C	6	0.1	31.13	0.4	21.65
D	**20**	**0.1**	**43.35**	**0.4**	**30.15**
E	**25**	**0.1**	**11.67**	**0.4**	**8.12**
Total (D+E)	**45**		**55.02**		**38.27**

8.7 Summary

The criteria for estimating CO_2 storage capacity in oil and gas reservoirs and saline aquifers are presented and sit screening is used to evaluate potential storage place in this study. Sites D and E are two candidates, in which the increased oil recoverable reserves are 4.3 Mt tons, CO_2 storage capacity in the reservoirs is 25.49 Mt tons. And CO2 storage potential in saline aquifers in D and E are estimated, the total storage capacity is 38 to 55Mt tons depending on the irreducible water saturation between 10 to 40 % in the aquifers. The distance between IGCC power plant, and D and E is 100 to 150 km.

9. ECONOMIC ANALYSIS FOR DEMONSTRATION PROJECTS

An in-depth financial analysis of the coal-fired power plants is carried out separately for an IGCC scheme with and without CCS. A potential demonstration project, Integrated Gasification Combined Cycle (IGCC) power plant (430MW) to be developed by GreenGen Co. Ltd under China Huaneng Group is assumed to be the objective for the analysis. Firstly a pure IGCC power plant without CCS was analyzed for the purpose of comparison. Then two CCS technical schemes based on 60% and 100% CO_2 capture with the IGCC power station, and relevant financial analysis outcomes were obtained.

A key indicator for financial viability of such a demonstration project is considered to be the electricity tariff or wholesale electricity price charged to the power plant, which is usually determined by the government. The outcome from the analysis is an expected electricity tariff under certain conditions. This approach aims to imply a bottom line tariff that the government would need to consider when making pertinent decisions for the demonstration project.

9.1 Technical Parameters in the Three Cases of the Demonstration Project

The technical parameters for the three cases, i.e., an IGCC power plant (430 MW) without CO_2 capture, an IGCC project (430 MW) with 60% CO_2 capture and an IGCC project (430 MW) with 100% CO_2 capture, are stated as Table 20.

Table 20 Technical Parameters of Three Cases of the Demonstration (based on currently available technology)

No.	Item	Unit	No CO_2 Capture	60% CO_2 Capture	100% CO_2 Capture
1	Coal type		Shengfu	Shengfu	Shengfu
2	Coal lower heating value (LHV)	MJ/kg	22.76	22.76	22.76
3	Coal feed	t/d	3280.8	3235.3	3332.4
4	Plant capacity factor	%	69	69	69
5	Number of operation hour	h/y	6,000	6,000	6,000
6	Gasifier type		TRIP, dry and powder feed	TRIP, dry and powder feed	TRIP, dry and powder feed
7	Gas turbine class		GE, F class	GE, F class	GE, F class
8	HRSG type		3-pressure single reheat	3-pressure single reheat	3-pressure single reheat

9	Gross power capacity	MW	430	430.0	426.3
10	Rate for self-used electricity (Auxiliary power ratio)	%	15.1	25.1	29.0
11	Net power output	MW	365.1	322.0	302.5
12	Net plant efficiency	%	42.3	37.8	34.5
13	CO_2 capture rate	t/h	n.a.	178.9	307.2
14	Mass of captured CO_2	Mt/y	n.a.	1.07	1.84

Source: GreenGen Co.

9.2 Project Capital Cost Estimation

The data of base capital costs for the three cases of IGCC plant is provided by IET and GreenGen Company as shown in Table 21.

Table 21 Base Capital Cost Estimation (US$ million)

Equipment/Units	IGCC		IGCC+60% CCS		IGCC+100% CCS	
	430MW	%	430MW	%	426MW	%
Air separation	56.1	9.8	55.7	8.8	56.6	8.4
Coal handling & Gasification system	164.5	28.8	163.0	25.6	166.2	24.6
Purify systems (including ash disposal, purification and desulfur units)	27.2	4.8	27	4.2	27.5	4.1
Shift unit	-		18.5	2.9	26.6	3.9
CO2 capture equipment		0.0	11.5	1.8	16.5	2.4
CO2 compressors		0.0	13.8	2.2	19.8	2.9
Combined cycle	189.3	33.2	187.5	29.5	191.3	28.3
Building of plant	95.1	16.7	110.3	17.4	117.3	17.3
Other costs (costs attached to the sites, including water supplement, foundation etc.)	38.3	6.7	48.2	7.6	54.3	8.0
Total static investment	**570.5**	**100.0**	**635.5**	**100.0**	**676.1**	**100.0**

A physical contingence rate 8% is applied to the base costs. The factors such as inflation rates and loan interest rates, used for calculation of price contingence and interests during construction are to be explained in the following section. As a result total capital costs for the assumed three cases are calculated.

9.3 Project Financing Structure

On the basis of the cost estimates, project financing is assumed to come from three basic sources: international loan and grant, local bank loan and owners' equity. The proportions among the three are to be approximately 20% equity financing, 30% international financing and 50% domestic loan financing.

Since no international fund specifically targeting to CCS can be envisaged at this stage, the ADB loan is regarded as the only source for international financing. The international capital is assumed to finance part of the component of equipment in the cost structure. The potential ADB loan would have a total loan period of 25 years including a grace period of 5 years. The schedule of loan principal repayment after the grace period is prepared with installment shares, which are determined on the annuity basis using a 10% discount rate as stipulated in the ADB guidelines. The financial expenses for the ADB loan compose a floating interest rate to be determined in accordance with ADB's LIBOR-based 10-year fixed swap rate (2.62% as of 18 Oct 2010), an ADB fixed spread component of 0.2%, and a commitment charge of 0.15% per annum. A floating interest rate for the ADB loan during construction was determined in accordance with ADB's LIBOR-based 5-year fixed swap rate (1.42% as of 18 Oct 2010), also with an added fixed spread component of 0.2%. The commitment charge would be incurred on the un-withdrawn portion of the loan on a yearly basis, while it was assumed the loan to be disbursed in proportions of 5%, 20%, 45% and 30% during the construction period.

The long-term domestic loan was basically assumed to have an 18-year loan period including 3-year grace period at a fixed annual interest rate of 6.14% (as of Oct 2010). It was assumed the loan principal would be repaid with an equal amount each year over the 15 years starting from the commencement of operation, whilst the associated interest would be paid annually. Working capital required for the operation is to be financed with short-term domestic loan, which would be renewed every year, at an annual interest rate of 5.56% (as of Oct 2010).

9.4 Assumptions for Financial Evaluation Factors

- The project was assumed to have a useful economic life of 20 years after commencement of operation with residual value being considered.
- The current official exchange rate between Chinese local currency and the US dollars is US$1 = RMB6.8 and was assumed to be constant during the project life.
- The local inflation rates are applied according to ADB's estimated domestic cost escalation factors over the project's first few years, while 3% of inflation rate is applied in a long run.
- The international inflation rates were again taken from ADB's estimated international cost escalation factors.

- The actual electricity tariff in the area where GreenGen is situated is RMB0.382/KWh (US$56.18/MWh), while RMB 0.5608/KWh (US$82.47/MWh) was permitted by the authority to be applied to the feasibility study for GreenGen IGCC phase 1 (250MW). Such a particularly permitted tariff is used in this report as a benchmark for comparison with various expected tariffs resulting from the analysis.
- The analysis assumed electricity to be the only product sold to the market. The financial analysis model could also be used to test financial results under different scenarios of CO_2 sale for EOR or through CDM[18].
- Assumptions for the operating expenses applied in the financial projection were as follows:
  - o The coal price was estimated to be RMB640/ton including 13% of value-added tax (VAT).
  - o Consumption of water in the production would be 0.3014 m^3/s.GW, resulting in an annual water consumption of around 2.6 million m^3. The water unit cost is currently RMB 8.33/m^3.
  - o Cost for materials was calculated to be RMB 12.53/MWh.
  - o Cost for other items including administrative expenses is estimated at RMB 10/MWh.
  - o The number of employees would be 300 with an annual average salary of RMB 45,000 per person. Salary-based welfare is 60% on the total salary.
- Different categories of fixed assets are depreciated using the straight-line depreciation method at different annual depreciation rates, with 2% for land use rights, 3.3% for civil works, 5% for equipment and 20% for engineering services and other fixed assets.
- The value-added tax (VAT) remains 17% on sales. The city maintenance and construction tax and education tax are charged at 7% and 3% on the VAT respectively. The project would be subject to the normal income tax of 25% annually. Within the capital costs, 5% construction tax on civil works and 17% value added tax on equipment value are adopted.
- Account receivable was assumed to be 3/12 of the gross sales.
- Inventory was assumed to be 4/12 of the fuel and materials costs.
- Account payable was assumed to be 3/12 of the operating expenses excluding depreciation and amortization.
- The annual maintenance cost for the CO_2 pipeline was calculated to be as much as 3% of the pipeline capital cost.

[18] At the present, CCS has not been considered to be included in the CDM by the UNFCC CDM EB.

- The CO_2 storage cost is calculated on the basis of US$20 per ton of CO_2 captured, which covers both the capital cost and maintenance cost. This is cited from a range of US$15-25/t estimated by a document "CO_2 Capture and Storage – A key Carbon Abatement Option" published by OECD/IEA.
- A 5% royalty fee on CO_2 revenue would be charged into the operational cost, in case the CO_2 could generate incomes through either EOR or CDM.

9.5 Main Findings

The purpose of the analysis was to show under what conditions a CCS demonstration project in China could be financially feasible, provided the government gives incentives. The following Table 22 indicates results from different scenarios or options calculated by the financial analysis model. The main findings are described below:

- While the current local electricity tariff RMB 382/MWh is set up for the power industry dominated by pulverized coal (PC) combustion plants, all the three IGCC schemes require higher tariffs to be financially sustainable because of lower energy efficiency of the IGCC plant and additional cost for CCS.
- The expected tariff of the IGCC without CCS scheme is below the benchmark tariff RMB560.8/MWh assumed in the feasibility study for the GreenGen IGCC phase 1. The expected tariff of the IGCC+60% CO_2 capture scheme is 14.2% higher, and the expected tariff of the IGCC+100% CO_2 capture scheme is 37.9% higher than the benchmark tariff.
- At the benchmark tariff, if the CO_2 captured by the power plant could be sold out at US$10 per ton for EOR, the expected tariffs for the two IGCC+CCS schemes could be determined lower than or close to the benchmark tariff. In other words, the IGCC+60% CO_2 capture scheme does not need to charge for CO_2 to be provided for EOR, while the IGCC+100% CO_2 capture scheme should charge $7.4 per tonne of CO_2.
- At the benchmark tariff, to make the project financially feasible the CO_2 price at the CDM or other carbon market mechanism would need to be at least $18.7/t for the IGCC+60% CO_2 capture scheme and $27.2/t for the IGCC+100% CO_2 capture scheme.
- At the benchmark tariff, to guarantee the return on investment the government needs to subsidize the project capital cost with $198.8 million for the IGCC+60% CO_2 capture and $498 million for the IGCC+100% CO_2 capture. Alternatively, the government has to subsidize the coal cost with RMB 148.3 million each year for the IGCC+60% CO_2 capture and RMB 371.4 million each year for the IGCC+100% CO_2 capture.

- If only the additional capital cost spent at CO_2 capture facility and transport pipeline ($110 million for the 60% capture case, $150 million for the 100% capture case) would be subsidized by the government or international climate change fund, the expected tariff would be reduced to 8.6% or 29.8% higher than the benchmark for the two cases.
- If the additional capital cost spent at the CO_2 capture facility and transport pipeline is to be subsidized, the income tax can be exempted, the expected tariff would reduce further to 4.6% or 25.6% higher than the benchmark for the two cases.
- If the additional capital cost spent at CO_2 capture facility and transport pipeline was to be fully subsidized and CO_2 could be traded at $20/t, then the expected tariff would become 10.7% and 2.3% lower than the benchmark tariff. In this circumstance the benchmark tariff could be applied to the IGCC+CCS schemes.

Table 22 Scenarios & Results with Different CO2 capture Rate (60% vs. 100%)

Scenario / Option	Indicator	Unit	60% CO_2 Capture	100% CO_2 Capture
No government incentive	Expected tariff	Y/MWh	640.6	773.4
	% as the benchmark tariff	%	114.2%	137.9%
At the current IGCC tariff, sell CO_2 for EOR	CO_2 price for EOR	$/t	0	7.4
At the current IGCC tariff, sell CO_2 through CDM	CO_2 price for CDM	$/t	18.7	27.2
At the current IGCC tariff, subsidize the capital cost	Value for subsidy	$ million	198.8	498.0
At the current IGCC tariff, subsidize the coal cost	Value for subsidy	Y million	148.33	371.41
Subsidize only the additional capital cost caused by CCS (excluding storage)	Expected tariff	Y/MWh	609.18	727.76
	% as the benchmark tariff	%	108.6%	129.8%
Subsidize only the additional capital cost, and income tax exempted	Expected tariff	Y/MWh	586.33	704.24
	% as the benchmark tariff	%	104.6%	125.6%
Subsidize only the additional capital cost, and CO_2 price at $20/t.	Expected tariff	Y/MWh	500.91	548.17
	% as the benchmark tariff	%	89.3%	97.7%

There are basically three policy tools that the government can use to encourage investment in CCS related projects, i.e., manipulation of the electricity tariff, subsidization of capital cost

and exemption of the income tax. It is reasonable and acceptable for the government to raise the tariff for a specific demonstration CCS project. It would also be understandable that free fund is provided to a CCS project to partially reduce the cost burden. In addition, some kind of carbon market system could be expected to come into force to benefit CCS projects sooner or later. How all the incentives are going to affect a CCS project depends on an optimal mixture of the various approaches in consideration of balancing different factors.

10. POTENTIAL OF COST REDUCTION FOR IGCC AND CCS TECHNOLOGIES IN THE FUTURE

High costs associated with the CO_2 capture, transport and storage are the main obstacle for the CCS demonstration. However, the potential of cost reduction for CCS exits in China, aa a result of the localization of technologies, efficiency improvement, reduced equipment manufacturing costs etc. This is in particular of importance for the future roadmap development for the demonstration of CCS in China.

10.1 Methodology

The experience curve or learning curve has been used for the analysis of the cost reduction in the future. Typically, the unit cost of a technology decreases with increasing diffusion of the technology into the market. The relationship between the cost of a technology and its cumulative production can be described mathematically by means of the following curve, the so-called learning curve:

$$C_{Cum} = C_0 C_{um}{}^{b},$$
$$\log C_{Cum} = \log C_0 + b \log C_{um},$$
$$PR = 2^b, \qquad (11)$$

Where C_{cum} is the cost per unit, C_0 the cost of the first unit produced, C_{cum} the cumulative (unit) production, b the experience index, PR the progress ratio, PR denotes the progress ratio, expressing the rate of unit cost decline with each doubling of cumulative production. For example, a PR of 0.8 implies that after one doubling of cumulative production, unit costs are reduced to 80% of the original costs. LR is cost learning rate, LR = 1-PR.

The cost learning curve of a technology depends on the cost learning rate and the current cumulative production and learning rate is particularly crucial. Equipment localization, single equipment scale, and energy penalty of CO_2 capture have great impacts on both total costs of the system with CO_2 capture and the CO_2 avoided cost. The learning rate of the energy system in this report was derived as:

$$LR = \frac{I_0}{C_0} LR_{inst} + \frac{(C_{OM})_0}{C_0} LR_{OM} + \frac{C_{Fuel}}{C_0} LR_E = \lambda_1 LR_{inst} + \lambda_2 LR_{OM} + \lambda_3 LR_E \quad (12)$$

where λ is the proportion of the cost of each part. The learning rate of energy system costs can be described further into detail as:

$$LR = \lambda_1 [1 - \frac{A}{A_0}(1 - LR_{inst,f})] + \lambda_2 LR_{OM} + \lambda_3 LR_E = f(A/A_0, LR_{OM}, LR_E) \quad (13)$$

The learning rate of energy system costs is related to equipment localization process ratio, the learning rate of equipment investment, the learning rate of operating and maintenance, total energy penalty of system and the learning rate of energy penalty.

10.2 Main Results

Table 23 displays the different localization level of some key parts in IGCC, from which we can see that ASU and Coal-water slurry gasification units are largely localized y, turbines and Pulverized coal gasification units are partly localized, and some key technologies haven't been mastered, for example, CO_2 capture units depend on importing completely.

Table 23 Statistics of localization level of the main equipments in IGCC

Unit	GT sets (6B)	ASUs	Coal-water slurry gasification	Pulverized coal gasi-fication	Desulfuriz-ation units	CO_2 capture units
Current Localization	auxiliary systems localized totally	R&D, design & manufacture independently	Domestic production except some individual valves	Water-wall of gasifier imported	Only catalyst imported	Imported totally
Cost Reduction	20%	50%–60%	50%–60%	25%	50–60%	5–10%
Data source	*These data from some related companies and institutes has not been published.*					

Table 24 shows the potential for the localization of the main components in IGCC. The coal dry pulverized gasification, combined cycle and CO_2 separation unit have high localization potential. If the localization is completed in the future, the IGCC and IGCC with CO_2 capture could reduce its investment by 22 -28%.

Table 24 The localization potential for key IGCC+CCS equipments

	Current localization	Mature level	R&D barriers	Localization potential
AUS	√√√√	√√√	√	Low
coal slurry gasification	√√√	√√	√	Mid
coal dry pulverized gasification	√√	√√	√	High
Combined cycle	√	√√	√√	High
CO_2 separation unit	√	√√	√	High

Considering the Tianjin IGCC demo project for example, the cost of IGCC can be reduced from about RMB 9800/kW to RMB 7300/kW by means of complete localization. It can be seen from Table 25 that without CO_2 capture, the biggest potential of investment decline lies in the combined cycle, which accounts for 52% of the total reduction (RMB 2523/kW). The total reduction will be higher (RMB 3222/kW), if CO_2 capture is considered. It means that the IGCC with CO_2 capture has greater localization potential.

Table 25 Analysis of investment reduction caused by the localization of each part in Tianjin IGCC demo project

	IGCC		IGCC+CCS	
	Investment decline (RMB/kW)	Proportion	Investment decline(RMB/kW)	Proportion
ASU	86	4%	102	3%
Coal Gasification and purification unit	1107	44%	1312	41%
Combined cycle	1330	52%	1576	49%
Single project related to site	-	-	232	7%
Other cost	0	-	0	-
Total reduction	2523	100%	3222	100%

Considering the different localization processes, apposite policy recommendations is given respectively. Under the different policy, the key equipments also have their own target as show in Fig. 22.

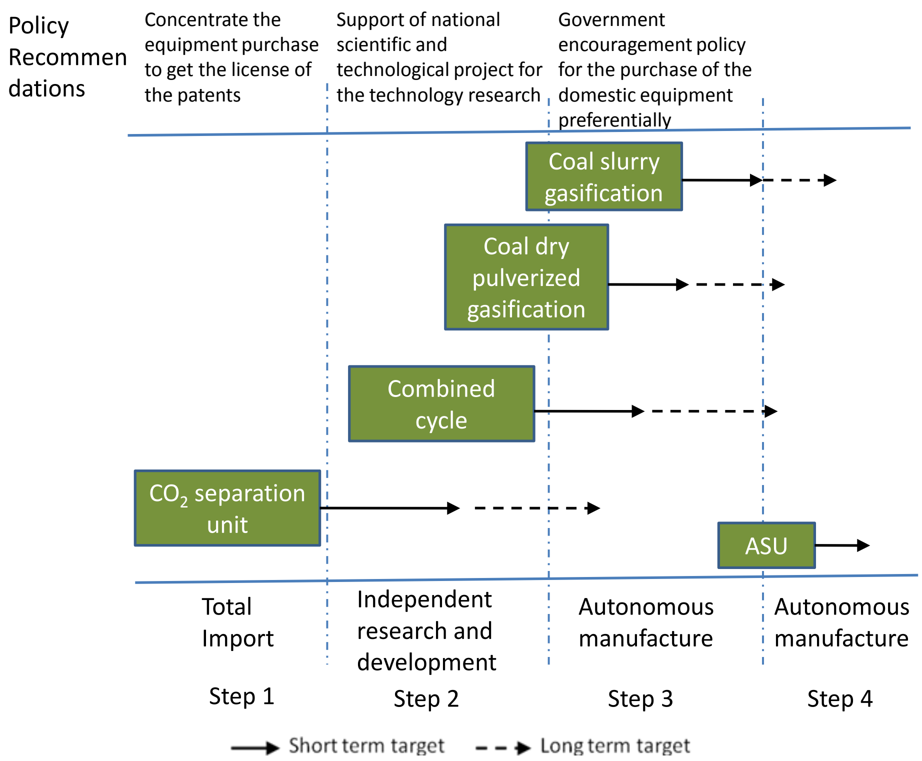


Figure 22 Localization development of key equipments

With the increase of installed capacity of CCS plants, the investment costs ($/kW) are expected to reduce as shown in Fig. 23. The model shows that the combined efforts of localization, technology diffusion and efficiency improvement make investment costs of IGCC with CCS decreased dramatically from the first demonstration plant. Up to 200 GW, IGCC+CCS becomes more attractive (ca 800 $/kW) compared to the technology option of the PC+CCS and CO_2 avoided cost can be reduced to about 25 $/t-$CO_2$ or lower (Fig. 24). Contributions to this reduced cost are from the decreased costs of equipment manufacture (40% to 50%) efficiency improvement (10% to 20%) and localization (15% to 35%). The COE of IGCC+CCS should also decline from the current 0.11 $/kWh to 0.06 $/kWh.

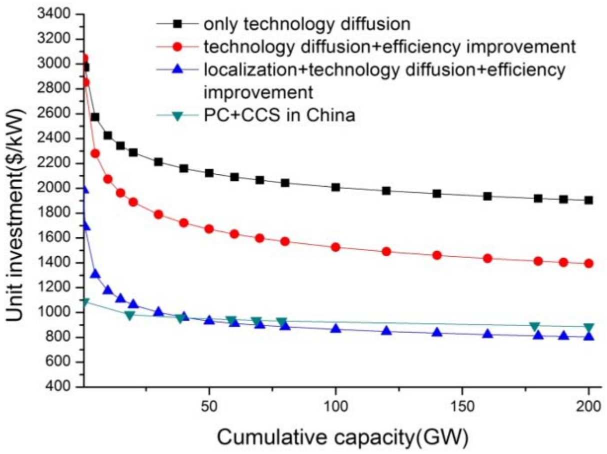


Figure 23 Investment learning for IGCC+CCS plants

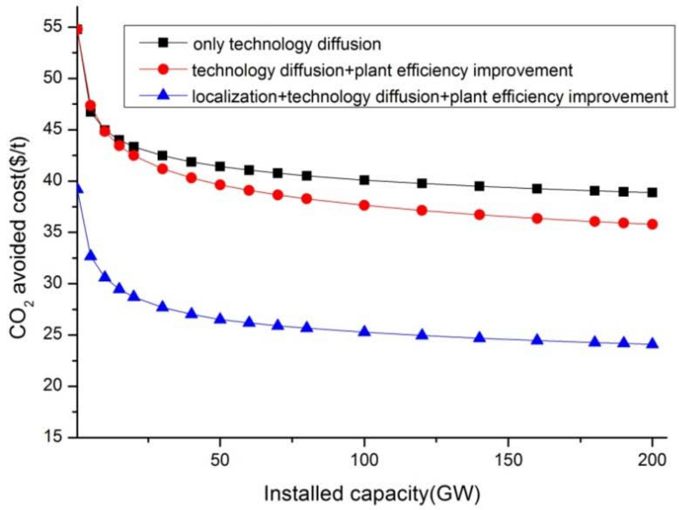


Figure 24 CO_2 avoided cost learning for IGCC+CCS plants

10.3 Summary

Findings:

- The learning effect and localization are the key factors for the cost reduction of IGCC + CCS. Compared with 38 $/t in USA, the CO_2 avoided cost of IGCC + CCS system in China is a bit lower but not obvious. But the investment cost of IGCC+CCS plant will be decreased to RMB 9000/kW after the entire localization. Gas turbine and gasification unit are the top two units in terms of localization potential, and their contributions account for 80 –

90% in the whole cost reduction of IGCC resulted from localization. Consequently, depending on the learning effect, efficiency improvement and equipment localization in China, the CO_2 avoided cost may drop from the current 38 $/t to 25 $/t in China in the future.

- Combined with CCS, IGCC may defeat PC plant after growth of installation capacity. Currently, the cost of IGCC is much higher than that of the PC, which is the major obstacle deferring the dissemination of the IGCC technology. Even if IGCC is fully developed, its advantage will not be obvious compared to the PCs. But if combined with CCS, IGCC+CCS would have a larger potential competitive advantage than PC+CCS. For IGCC + CCS systems, when cumulative capacity reaches 200 GW, through technological diffusion, localization and other means, the unit investment of IGCC+CCS in China may drop from the current 2000 $/kW to about 800 $ / kW and the COE can also decline by more than 50%, which is superior to PC+CCS plant.
- Lower energy penalty will be the crucial advantage of IGCC+CCS compared to PC+CCS. This may be the key point makes the CCS technology be sustainable and acceptable to China. Solely from the viewpoint of economic, IGCC+CCS technology may not good enough to replace the role PC+CCS in foreseeable future. However, with lower energy penalty and bigger potential for efficiency improvement compared to that of PC+CCS, IGCC+CCS can save billion tons of coal in scenario with CO2 emission control, which will be the crucial advantage helping IGCC+CCS plant become the dominating power generation technology of China in future.

Recommendations

- With advanced technical performance but rather higher investment cost, IGCC technology is difficult to be competitive to PC technology in near term. However, the requirement of adopting CCS technology will change this situation, which makes IGCC+CCS become techno-economic superior to PC+CCS plant gradually. For this aim, special attention should be paid to location of key equipments including gasification, CO2 separation and gas turbine, whose cost may cut down significantly. Meanwhile, the policies specific for promoting the technology transfer, independently develop, and technology demonstration should be issued, which will finally drive the decarburization of coal relied power industry of China.

- The first demonstration project of IGCC+CCS will be critical step influencing the development of this technology, but rather high additional cost due to CCS is one of the major concern of project owner. To overcome this problem, the economic burden of demonstration project should be taken by multi-efforts including government, industry and related international agency. The effective cooperation and joint financial mechanism should be setup before the construction of first CCS demonstration project.

- To the present, there is still no clear answer to the question that which CCS technical direction is more suitable and acceptable for China. Compared to PC+CCS, IGCC+CCS has attractive potential in economic performance, and more important, better performance in energy utilization efficiency. Considering the dominating role of PC plants, and the tendency of low carbon technology facing China, it is urgent to identify the main technical direction and the technical high land of power sector. In-depth research that can judge the role of IGCC+CCS and PC+CCS in CCS roadmap of China should be carried out.

11. GOVERNMENT INTERVENTION ON POLICY AND REGULATORY FRAMEWORK IN CCS

11.1 Policy options

Climate related policy and strategic documents in China are listed in Table 26.

Table 26 Policies and regulations in associated with CCS in China

Policy and/or regulations	Explanations
China's National Climate Change Program	This program was issued by the State Council on 4th June 2007. The objectives, principles, priority areas and countermeasures, positions, and demands for international cooperation for addressing climate change by 2010 are stated in this Program.
China's Scientific and Technological Actions on Climate Change	This program was issued by the Ministry of Science and Technology (MoST), together with 13 other ministries and departments, on 14th June 2007. The objective of this program is to coordinate climate change-related scientific research and technological development, and to enhance the comprehensive S&T (science and technology) capacity in response to climate change.
The Outline of the National Program for Medium- and Long-term Science and Technology Development (2006-2020, PRC)	This Program identified guidelines, objectives, and a general layout for China's science and technology development 2006-2015. CCS was highlighted in the Program as a frontier technology, while 'Development of efficient, clean and near-zero emissions fossil energy technology' was listed as a key component in the advanced energy area.
National Outline for CCS Technology Development	MoST is now developing a national outline for CCS technology development in China, which will be an important document of CCS technology policy. The outline aims to define a roadmap that will instruct the development and implementation of CCS technology, including the objectives and directions of CCS technology in the near future (up to 2030), major fields for research and development of CCS technologies, key tasks during the 12th FYP (five year plan), and potential demonstration projects.

In order to promote CCS demonstration and deployment, many governments are considering a range of policy options for meeting the cost of CCS, all of which require Government intervention in the market place. These include:

- Cap and Trade. Companies are given CO_2 emissions quotas. If a company exceeds its quota then it has to buy more emissions permits from a company that has not used its allocation up. Hence the permits have a value and can be traded, such as in the European Emissions Trading Scheme (ETS).

- Tax CO_2 emissions. This puts a value on all CO_2 emissions to the atmosphere, hence it may become cheaper to capture the CO_2 and store it. The Norwegian Government has used this approach.
- Limit CO_2 emissions from power stations in terms of the amount of CO_2 per unit of energy generated. For example, power stations could have a maximum emission limit equivalent to a state-of-the-art gas-fired plant. CCS would therefore be required for coal-fired plants (which emit much more CO_2 than gas-fired plants), and this would be paid for by the price difference between gas (expensive) and coal (cheap).
- Direct Government subsidy. In this method, a private company, or a coalition of power generators, pipeline owners and oil companies, are given the cost difference between the price of building a new conventional fossil-fuel power station, and one with CCS. The difference in operating costs would also be compensated. This is the approach the UK Government is using in the competition to build the first UK CCS scheme.
- Government planning and roadmap for CCS development and diffusion in China. By recognizing the importance of CCS for CO_2 mitigation, and technology competitiveness, CCS could be included in the national planning.
- Legislation directly requiring all new power-stations to have CCS installed and in operation.

11.2 Regulatory framework

Ultimately a coherent policy and regulatory framework is required as this will affect the operating basis of the companies that own coal fired power plants. For example, since newly-constructed power plants typically operate for 40 years or more, operators and investors desire some level of certainty regarding future regulatory demands in order to effectively plan future generating capacity. In the absence of firm regulatory requirements, utilities that have plans to build new coal-fired plants may decide to switch to alternative technologies or delay construction until the situation is clarified. In order to limit such uncertainty, the European Commission has set out a clear timetable over which it expects CCS to be established. Certain nation states such as the UK have gone further with the introduction of a new regulatory system, which requires all newly built coal power plants to capture at least 20-25% of their emissions as soon as they start operation. An upgrade to full capture capacity will then be expected to be in operation within five years of CCS being independently judged as technically and commercially proven.

China has an opportunity to observe and draw lessons from the experiences of other countries in deciding how it wants to proceed in developing regulations. At the same time, it is important to recognise that these regulatory frameworks are being prepared by nations that expect to establish a legal basis for the commercial deployment of CCS, with the likely date for widespread application being 2020 onwards. Thus regulation for demonstration plants is being developed in parallel to policy initiatives and requirements to subsequently deploy CCS systems at power plants. At present, China is taking steps towards establishing a CCS demonstration project but without the longer term commitment to CCS commercial deployment. This does not offer the stability that a utility or major industrial process operator would need to make robust future investment decisions.

11.3 Reducing risk and uncertainty through demonstration

The other point to recognise is that technology demonstrations are undertaken to reduce technical and economic uncertainties such that commercial deployment can subsequently be undertaken. As such, it is important to recognise that the results arising should allow greater clarity to be determined regarding the level of risk for different systems through interpretation of the knowledge gained from demonstrations and also from early technology deployment. Thus it is important that any regulatory framework established such that CCS demonstrations can proceed, provides a balance between stability and predictability with flexibility and adaptability to new scientific and technical information. For example, during the demonstration and early deployment of CCS, plant operators will need to work with scientists to closely monitor and understand the full range of environmental impacts and risks arising. In turn, regulators should be adaptive in setting long-term emission standards only when the results of such evaluations are available.

It should also be noted that several demonstrations of each key technology variant (i.e. post-combustion, pre-combustion and in due course oxyfuel) are needed at power plants to provide the critical information needed to overcome the current lack of factual knowledge about risks for each CCS component (capture, transport and storage) and to better understand the issues associated with integration of CCS as a whole. Thus if such data and risk estimates can be made public, rather than be classified as proprietary, the overall value of the information will be enhanced. It will also help overcome the issues concerned with

public perception and the acceptability of risk. The EC-sponsored CCS demonstration network (www.ccsnetwork.eu) is a good example of such an approach, for which it could be appropriate to expand membership to include China. Since the responsibility for establishing full-scale demonstration projects lies primarily with national governments, who will almost certainly be sharing in the funding of these demonstration projects, they should be able to overcome any reticence from industry about working on a collaborative basis.

11.4 Legislation related to CCS chain

In terms of specific instances where existing Chinese legislation might be adapted to establish CCS regulations, firstly, the classification of CO_2 is important because it will define which existing regulation might be most relevant, depending on whether CO_2 is defined as a waste or as an industrial product. Impurities present in the CO_2 stream may well influence its definition. The European Commission is strongly of the view that CO_2 should be considered as an industrial product. Working on the assumption that this position could be adopted globally, the following points should be considered further:

- For CO_2 capture, the 'Environmental Impact Assessment Law' in China could well be appropriate while the 'Prevention and Control of Atmospheric Pollution Law' could provide the legal basis for preventing and controlling non-CO_2 emissions from CCS facilities. This also considers liability in detail and so may be useful in drafting appropriate legislation on this particular issue. The 'Prevention and Control of Solid Waste Pollution Law' could serve as a legal basis for drafting regulation related to preventing and controlling solid waste (but not CO_2 itself) from the CO_2 capture facilities.

- Considering CO_2 transport, the 'National Standard of CO_2 Composition for Industrial Uses' and the 'Safety Management Regulation for Dangerous Chemicals' could be useful in regulating the safety and risk management of CO_2 transport.

- For CO_2 storage, the existing EOR regulations could be useful. However, since the purpose of EOR is to enhance oil recovery rather than store CO_2, there would also be a need to cover the management of CO_2 stored and the associated safety concerns. The regulation on 'Environmental Protection and Management for Oceanic Oil Exploration and Development' and the 'Mineral Resources Law' could both be adapted for developing regulation on CCS exploration permits. The 'Prevention and Control of Radioactive Pollution Law' could be used as the framework for future CCS regulation

relating to liabilities, site selection and site monitoring. This would include the ownership of the subsurface; ownership of the injected CO_2 and access rights; the responsibility of the operator to the storage site after closure, including definition of a 'transfer-of-responsibility' period.

- Identifying the parameters to be measured and monitored and the acceptable accuracy of instruments used are important. However, no restrictions should be imposed on which techniques should be used and operators should be able to select their own monitoring techniques provided that they meet the criteria set by regulation.

- Financial issues are important when considering liabilities and post-closure costs. Financial responsibility and commitment should be provided initially in the application for storage permits. Financial issues should cover the operation of the site (including change of ownership) and the closure and post-closure periods.

- With regard to how such regulation of CCS in China might be implemented, this could require both an energy authority and an environmental authority. The main authority responsible for permitting CCS projects in China is likely to be the National Development and Reform Commission (NDRC). The National Energy Bureau, which is part of the NDRC, may be responsible for issuing exploration and storage permits while the Ministry of Environmental Protection may be responsible for EIA and monitoring issues.

12. CLIMATE FUNDING OPTIONS FOR THE CCS DEMONSTRATION PROJECTS IN CHINA

The objective for the assessment of international funding mechanisms, including CDM, CIF, etc, is to analyze the needs and potential funding supports for preparing a bankable demonstration project for CCS demonstration in China.

12.1 Current funding mechanisms

New climate-related funding mechanisms covering both climate change adaptation and mitigation can be regrouped:

- By the source of funding: Mechanism funded by international public contributions which cover the majority of the existing mechanism and those that rely on market-based carbon finance.

- By their government structure: Funds coordinated under the authority of the UNFCCC / Kyoto Protocol and those that are either being managed directly by the funding bilateral agencies or administered by the World Bank and other multilateral agencies. Besides, there are several funding initiatives that are managed outside the UNFCCC's coordination.

At present, there are four multilateral funds under the UNFCCC: The Global Environmental Facility (GEF), the Special Climate Change Fund (SCCF), the Least Developed Countries Fund (LDCF) and the Adaptation Fund (AF). There are three funds which are managed by the GEF:

- GEF Trust Fund: The Common funding resource of the GEF. Climate change is one of the six focal areas supported by the GEF Trust Fund. The main objective is to assist developing countries to contribute to fulfilling the targets of the UNFCCC.

- Special Climate Change Fund: Its main objective is to fund projects directed toward capacity building, technology transfer and climate change mitigation.

- Least Developed Countries Fund: It was designed to help the LDCs covering their costs of preparing and implementing their National Adaptation Programmes of Action (NAPAs).

Funding initiatives that are managed outside of the UNFCCC's coordination are much larger in terms of volume and designed to address both adaptation and mitigation challenges, such as the Strategic Climate Fund (SCF), Clean Technology Fund (CTF), Carbon Partnership Facility (CPF) under the administration of World Bank, the EU-Global Climate Change Alliance, the Japan Cool Earth Initiative, the UK Environmental Transformation Fund, the Germany International Climate Initiative, etc.

12.2 Key criteria for the selection of climate funds for CCS demonstration

Four comparison elements and grading criteria are employed for the selection of funds that might be suitable for the CCS demonstration project in China as shown in Table 27.

Table 27 Criteria for the Selection of Climate Funds for CCS Demonstration in China

Criteria	Explanations
A. The prioritized areas of the funds	Dedicated climate funds with high priority for the demonstration and implementation of CCS technologies, for example, the ADB CCS Fund shall be considered.
B. The funding scale	CCS projects are often in large scale and have higher operating and capital costs, requiring incentives to build and run these facilities before they become economically competitiveon a broad scale. Therefore, the climate funds should be able to supply sufficient funding as needed for CCS demonstration projects. It is often difficult to receive financial support from one single climate fund to meet the needs of a CCS project. Therefore, several climate funds would needed simultaneously to support aCCS demonstration projects.
C. Economic power of target countries	Funds aiming at the developing countries or countries with economies in transition shall be considered for the CCS demonstration project in China for financial assistance.
D. Experience for supporting CCS demonstration projects	The existing climate funds that have supported the CCS demonstration projects shall be considered, for instance, the Global Environment Facility (GEF) Trust Fund, CTF and ADB CCS Fund.

12.3 Assessment results of the climate funds

By analyzing the above four factors, the Clean Technology Fund (CTF), GEF Trust Fund, the CCS Fund under ADB by Australia, and Global CCS Institute are the proper climate funds that are most appropriate for the IGCC-CCS demonstration project in China.

The Clean Technology Fund is designed to help the developing countries transit to the climate-resilient low-carbon developing mode through the multilateral development banks. The total amount pledges by the thirteen developed countries to the CTF is about US $ 4, 297 million s of 31st December, 2009. After analyzing the projects that the Clean Technology Fund (CTF) has supplied grants and loans to, the application scale of US $ 200 million seems appropriate. The application time is at least 2 years and the application document is titled Investment Plans.

The Global Environment Facility provides grants to developing countries and countries with economies in transition for projects related to biodiversity, climate change, etc. The Global Environment Facility has supplied grants to some CCS projects in some developing countries. We suggest an application scale of US $ 3 million would be appropriate. The application time is at least 2 years and the application documents are a Project Identification Form and Program Framework Documents.

The Australian Government has signed an agreement with the Asian Development Bank (ADB) to put AUS $ 21.5 million towards carbon capture and storage projects in Asia. The funds will support the Carbon Capture and Storage Fund. The new Carbon Capture and Storage Fund is part of the ADB's Clean Energy Financing Partnership Facility (CEFPF). Since its establishment in 2007, Australia, Japan, Norway, Spain and Sweden have committed $60.2 million to the CEFPF to support clean energy projects in developing countries. ADB has a target of $1 billion clean energy investments, which is going to be increased to USD 2 billion in 2013. An application on the scale of US $ 10 million seems appropriate. The application time is at least 2 years and the application documents are an application form and a draft concept paper.

The Global CCS Institute expects to make available approximately AUD $50 million annually to directly fund and support a substantial portfolio of CCS projects around the world. It calls for project funding applications which could be considered for single or multiple years of funding to allow for greater flexibility in the total amount of funding that can be sought by each applicant, and to focus on the different stages and specific needs in developing a project. The application scale of US$42 million seems appropriate. The application time is several months and the required documents are an application form and additional information.

12.4 Arrangement of the Application for the Climate Fund

The timeline for the selected four climate funds can be divided into three phases, i.e., Phase I -preparation of the documents and domestic approval, Phase II- Project cycle, and Phase III - implementation, monitoring and assessment as shown in details in Table 28 and Fig. 25.

Table 28 Timeline of application for each climate fund

	Phase I Preparation	Phase II Project Cycle	Phase III Implementation
Global Environment Facility	2010-2011 (one and a half year) Project Application Form to Ministry of Finance (MOF) through related industry central administrative department or provincial finance and administrative departments, and report to the Ministry of Environment Protection (MEP)	2012-2015 (3 years) Project Application Form to GEF administrative units, and implementation of the application according to the cycle of the GEF and related executive agency	2016-? Implementation, Monitoring and Assessment
ADB CCS Fund	2011 (six month) At beginning of each year, MOF and NDRC send a list of prioritized project proposals for the Facility Manager for inclusion in the Annual Work Program and prepare the application form and draft concept paper	2011-2012 (2 years) Review, comment, endorsement and approval of application documents	2013-? Implementation, Monitoring and Assessment
Global CCS Institute	2010 (about 1 month) Application form and project proposals, under leadership of NDRC-ERI	2010 (about 3 month) Assessment against eligibility and selection criteria and if approved, the project will be contracted by the Global CCS Institute	2011-? Implementation, Monitoring and Assessment

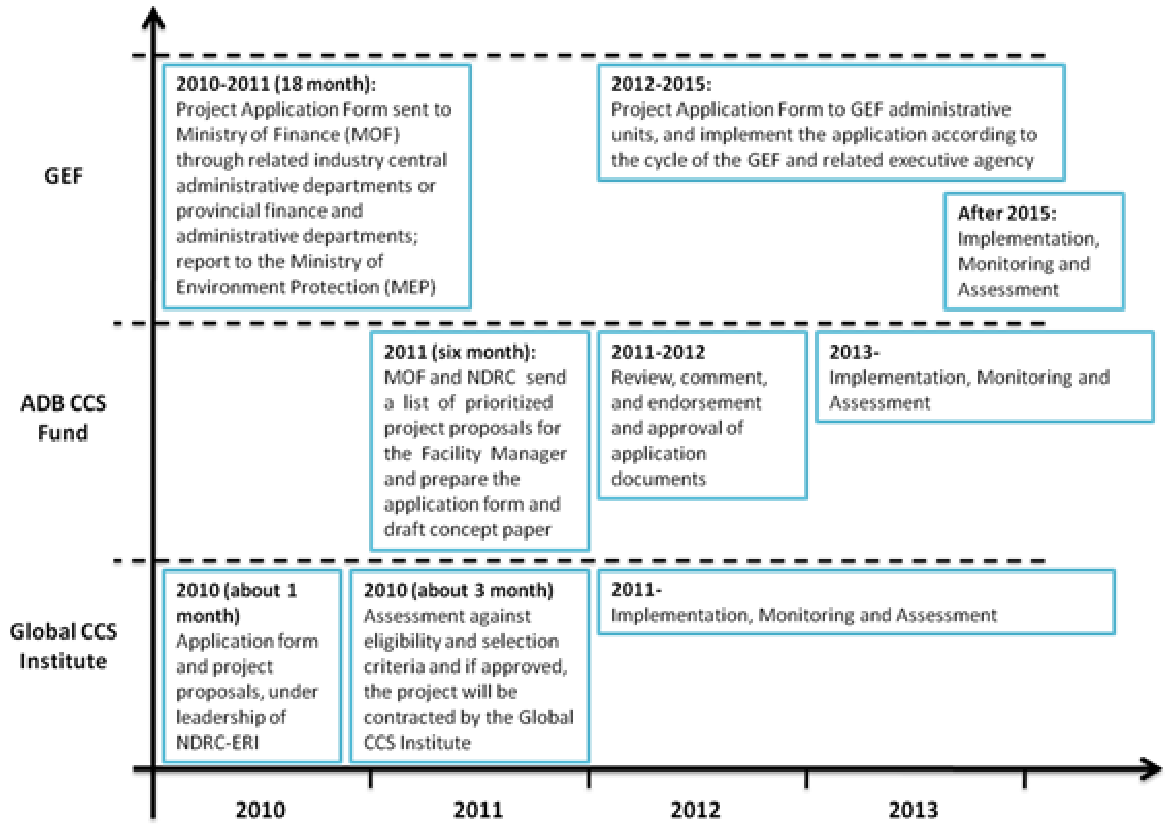


Figure 25 Timeline for preparation of climate funds

12.5 Funding Recommendations

- *Apply for the existing funds:* Although the existing funds only might cover a small share of the additional costs caused by the project, we suggest keep applying for those funds. Combined with other funding sources (like CDM) the funding challenge might be met after these mechanisms become more concrete than they are now.

- *Look for new funds:* Apart from the existing funds, it's also important to look at potential future opportunities. According to the Copenhagen Accords, the Parties agreed that there shall be funds ("Copenhagen Green Climate Fund") provided to developing countries for the purposes of financing emission mitigation, adaptation and transfer and development of low-carbon technologies. For 2010 to 2012, USD 30 bn is committed; by 2020, this amount will be raised to USD 100 bn annually. We suggest strongly focusing

on these funding opportunities and apply for them when their basic conditions and procedures become clearer.

13. INSTITUTIONAL CAPACITY EVALUATION AND STRENGTHENING

As set out in the project plan, existing institutional capacity and readiness of stakeholders to support the proposed GreenGen Tianjin IGCC+CCS demonstration project were assessed, including the analysis of GreenGen's company structure, shareholder conditions, cooperative objectives and goals, management team, national strategies etc. Based on the results from other work-packages in the project, selected institutional skills and resources needed to implement the CCS demonstration project were outlined and described. Then an institutional capacity gaps analysis was undertaken. The national and international knowledge and experts' networks required to support the CCS project are also listed. The results from the assessment of institutional capacity strengthening and recommendations are summarized, and finally measures to enhance awareness of CCS in public are identified in this chpater. The scope of the capacity study on the CCS demonstration project is shown in Fig. 26.

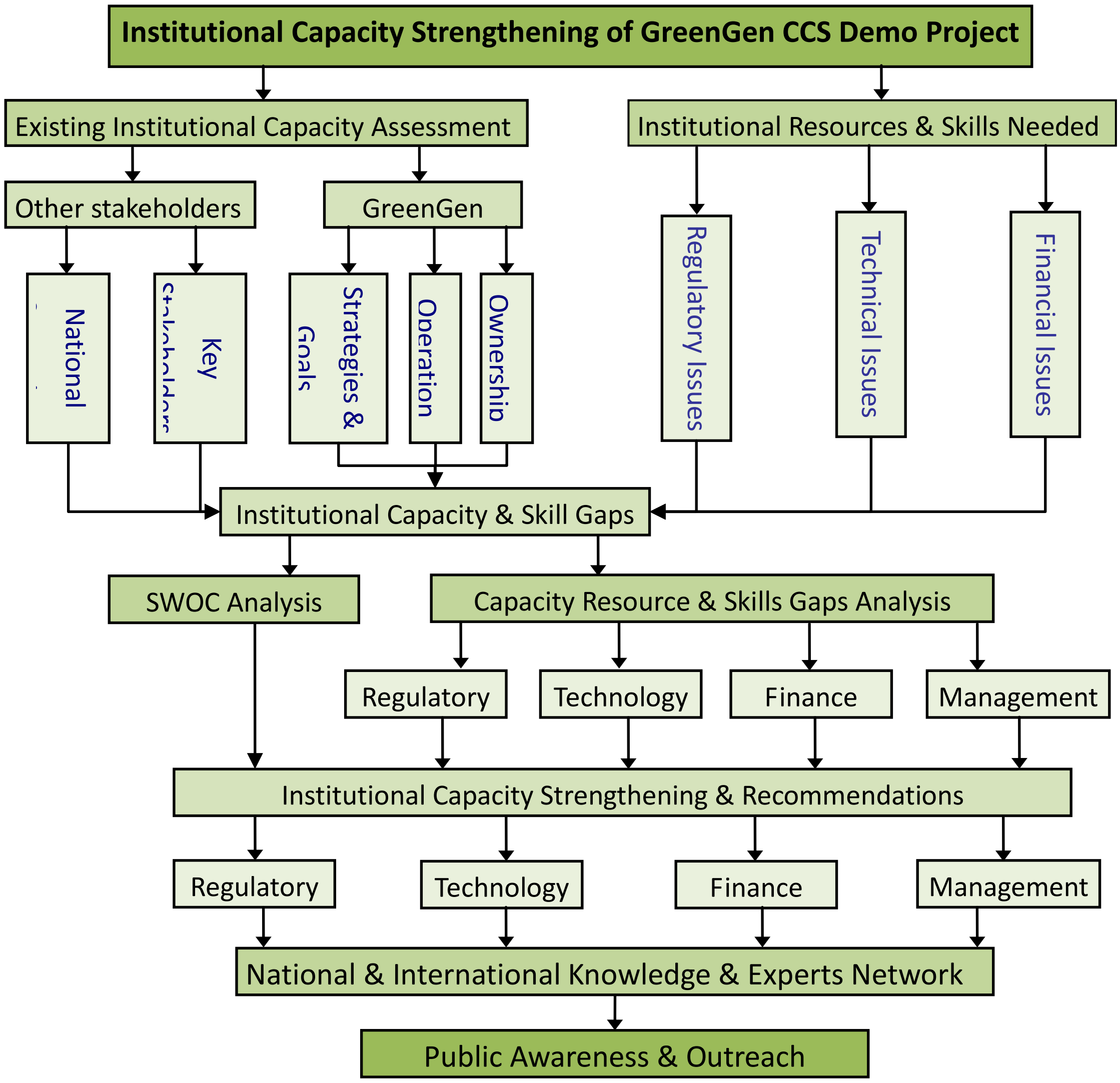


Figure 26 Institutional Capacity Analysis Program

13.1 Assessment of existing institutional capacity and readiness of stakeholders

GreenGen – The Project Implementing Agency (IA)

The GreenGen Corporation Limited (GreenGen) was founded on December 23, 2005. The company has been approved by the State Administration of Industry and Commerce (SAIC) with a registered capital of RMB 300 million. The Tianjin IGCC+CCS demonstration project is one of GreenGen's key projects with significant internal investment (GreenGen funding accounts for 75% of the total investment) and external investment from Jingneng Investment Co., Ltd (25% of the total investment).

GreenGen's shareholders include the China Huaneng Group (CHNG), the China Datang Corporation, the China Huadian Corporation, the China Guodian Corporation, the China Power Investment Corporation, the Shenhua Group, the China National Coal Group, the State Development and Investment Corporation, and the US Peabody Energy. CHNG is the largest shareholder with 52% of the total investment, and the other eight companies hold 6% equity each.

Research and design institutes

The national intuitions including engineering design institutes and R&D organizations are listed in Table 29.

Table 29 National design institutions and R&D organizations

Related national design institutes	Other technical support institutes & research organizations	Industry
Tianjin IGCC power plant: Designed by • Northwest Power Design Institute • Xian Thermo Research Institute • Ningbo Engineering Company of SPC **Reviewed by** Chemical Engineering Planning Institute of China Power Engineering Consulting Group	• The Institute of Engineering Thermophysics, Chinese Academy of Sciences • The Xian Thermal Power Research Institute, China • The Institute of Geology and Geophysics, Chinese Academy of Sciences • Tsinghua University • Research Institute of Petroleum Exploration & Development (RIPED), PetroChina • Zhejiang University • Huazhong University of Science and Technology • China Petroleum University • Huabei Power University • Wuhan University	• PetroChina • China Petrochemical Corporation (Sinopec) • China Huaneng Group (CHNG) • China Huadian Corporation • China Guodian Corporation • Shenhua Group

Several large CCS research projects have been finished or are underway in China. Both the National Basic Research Program (973 Program) and National High-Tech Research and Development Program (863 Program) include CCS R&D projects. At the same time, a number of Chinese institutes also took part in international cooperation on CCS projects.

13.2 Institutional Skills and Resources Needed to Implement the Proposed CCS Roadmap

The existing regulations relevant to CCS include The Environmental Impact Assessment Law and the Prevention and Control of Atmospheric Pollution Law, which provides the regulatory basis for the construction of large engineering project including CCS. However, as CCS is still

in the early stages of development, many detailed regulations or rules through the whole chain of CCS including capture, transportation and storage still need to be established. In addition, risk assessment of the CCS project needs to further investigation. Although the EU project, STRACO2, includes cooperation with China, China still needs to develop their own CCS related regulations to guide the implementation of CCS projects. International regulatory frameworks for the CCS have been initiated and established in Australia, EU, UK, and US as shown in Table 30. The international experiences can be helpful for the establishment of China's CCS regulations but the regulatory framework for China needs to be designed specifically for implementation in China.

Table 30 International regulatory framework in CCS

Country	Regulatory Framework
Australia	Australian Regulatory Guiding Principle Offshore petroleum amendment Act 2008 Australian Greenhouse Geological Sequestration Act 2008
EU	EU directive 2009/31/EC EU Directive 2008/1/EC Council Directive 85/337/EEC
UK	UK Energy Act 2008
US	IOGCC Guidelines American Clean Energy and Security Act EPA Guidance under the Underground Injection Control Program 2007

13.3 Gaps Analysis of Institutional Capacity and Resource

A summarized SWOC analysis of the implementation company, GreenGen, for the first demonstration CCS project is given in Table 31.

SWOC Analysis

A synoptic examination of Strengths, Weaknesses, Opportunities and Constrains about institutional capacity was undertaken with respect to the GreenGen Company and the development of the proposed GreenGen IGCC+CCS demonstration project.

Table 31 SWOC analysis of the implementation company GreenGen

Strengths	Weaknesses
▪ Strong government background. ▪ Strong supports from Huaneng Group and other relevant shareholders. ▪ A number of world class research institutes and universities participated in its case studies. ▪ Clear enterprise objectives and goals. ▪ Reasonable enterprise organization and	▪ The first CCS demo project in China. ▪ Lack of engineering experience in CCS. ▪ High investment and operation costs. ▪ Lack of coordination mechanism among different stakeholders for the whole chain of CCS ▪ Immature technologies.

▪ ownership structure. ▪ Seasoned & capable management team. ▪ A group of highly educated and capable staff. ▪ Existing international experience. ▪ Existing national and international cooperative research efforts/programs. ▪ Well designed and well prepared. ▪ Multi financing mechanism.	▪ Immature technical standards in engineering design and O&M. ▪ Potential risks in CO2 transportation and storage. ▪ Relatively complex equipment and larger operation crew (including the pipeline and storage maintenance and monitoring). ▪ Lack of relevant local policies and legislations. ▪ Existing financing bottleneck. ▪ Public awareness and acceptance.
Opportunities	**Constraints**
▪ Global awareness of GHG emission to climate change. ▪ Global requirements of CO_2 emission reduction. ▪ China's new Energy Saving and Emission Reduction Target. ▪ Chinese government is realizing that CCS is one of the effective potential GHG emission reduction methods. ▪ Increasing trend in the researches and practices of CCS both nationally and internationally. ▪ Potential direct financing support from multiple international agencies. ▪ Potential technical support from multiple international agencies. ▪ With the development of science and technology, the CCS technology will mature and its cost will reduce.	▪ Currently China has no clear plan for large scale CCS deployment unlike other countries that are planning demonstration projects. ▪ Higher investment and operation cost. ▪ Potential risks in the CO_2 transportation and storage. ▪ Difficult for project to be economically sustainable without tariff or financial support for enterprise in the market. ▪ No apparent financial advantage when compared with other new energy options such as nuclear power, offshore wind power, PV, SC/USC with capture. ▪ The lag of relevant regulatory policies or rules or standards. ▪ Lack of detailed geological storage information and issues in getting such information from relevant agencies/companies. ▪ Long term environmental and social impact assessment.

Gap analysis has been conducted on the institutional capacity and resources in the following aspects:

- **Strategic and legal framework**: Currently China has no regulatory framework on capture, transportation and underground storage of carbon dioxide. One option for China is to develop its regulatory framework guidelines in advance or in parallel with the technical studies to facilitate the deployment of CCS technology. Another option is to focus its efforts on developing CCS technology to reduce costs and energy penalties before addressing policy and regulatory barriers. For the implementing agency, in order to facilitate the CCS demo project, GreenGen would need to mobilize part of its resources to study relevant international regulatory rules associated with Chinese conditions. In the meantime, the experience of the demonstration project should be helpful for the government while establishing the CCS regulations.
- **Technical capacity:** Although R&DD in CCS are very active internationally, the technology is still new. The technical capacity in engineering, construction, operation and

maintenance, monitoring etc needs to be developed not only in China but also worldwide. There are still some outstanding issues for the implementation developer such as GreenGen to be solved, for example, lack of engineering experience and technical standards, design guideline, O&M procedures etc.

- **Multi-financing mechanism**: Higher investment cost and operational energy penalties remain one of the key barriers to economically sustainable CCS projects globally. How to set up the incentive policy and funding mechanism in China for CCS implementation is one of the important issues that need to be further addressed.
- **Project management**: GreenGen has great experience of normal coal-fuelled power plants, but China has almost no engineering experience in CCS, which will be a major barrier to the smooth construction and operation and maintenance of the GreenGen CCS demo project. As the first CCS demonstration project in China, GreenGen should cooperate with national and international agencies to explore every possibility, for example participation in international study tours and staff training programs to learn international CCS engineering experience and management skills worldwide. It is quite necessary for the Chinese government to establish a powerful agency composed of different key stakeholders to coordinate all stakeholders related to the whole chain of CCS. It is also important for GreenGen to set up an inner special department to deal with the coordination problems.

13.4 Recommendations on Institutional Capacity Strengthening

Based on the above evaluation and analysis, a summary of institutional capacity strengthening and recommendations to the GreenGen IGCC+CCS demonstration project is provided in Tables 32 to 35.

Table 32 Strategic and legal framework aspect

Current Status in China	International position	Gaps analysis	Recommendations
Related policies: • China's National Climate Change Program • China's Scientific and Technological Actions on Climate Change • The Outline of the National Program for Medium- and Long-term Science and Technology Development Limited relevant industrial & environ. rules	**Australia:** • Australian Regulatory Guiding Principle • Offshore petroleum amendment Act 2008 • Australian Greenhouse Geological Sequestration Act 2008 **EU** • EU directive 2009/31/EC • EU Directive 2008/1/EC • Council Directive	• China currently has no policy that directly deals with CCS • Currently China has no regulatory rules on CO2 capture, transport & storage. • There is a heavy lag in this aspect in China although there are several indirect policies and regulations which	• Both Chinese gov't & GreenGen should start now to mobilize part of their resources to study relevant international regulatory rules under Chinese conditions, and to develop China's CCS regulatory framework guidelines in advance or in parallel with demo project.

• The Environmental Impact Assessment Law • The Prevention and Control of Atmospheric Pollution Law. • National Standards of CO2 composition for Food Industrial Uses • Safety Management Regulation for Dangerous Chemicals	85/337/EEC **UK** • UK Energy Act 2008 **USA** • IOGCC Guidelines • American Clean Energy and Security Act • EPA Guidance under the Underground Injection Control Program 2007	could be referenced or transferable.	• The demo project experience can in turn provide useful advice to the government in the drafting of national CCS regulations in the future.

Table 33 Institutional recommendations to enhance the technical capacity

Current conditions	International position	Gaps	Recommendations
• There are some existing CCS research institutes, universities and experts • Existing national and international cooperative research efforts/programs • Experimentally, Chinese scientists have mastered technologies in the major aspects of CCS. • No engineering experience and no CCS demonstration projects	• Lots of CCS research institutes and experts • Lots of international cooperative research efforts/programs • Strong technical background in all CCS process • Long time relevant engineering experiences • Several CCS demonstration scale projects	• Ttechnical background not as developed as in some other countries • Immature technical standards in engineering design and O&M • Immature dedicated R&D with special considerations of China's conditions • No engineering experience • No demonstration projects	• Establishment of prompting mechanism to facilitate the technical research in CCS • Further encouragement and promotion of CCS research nationally & internationally to master the advanced technologies and gain engineering experience. • Cooperate with international agencies to gain the engineering experience. • Cooperate with ADB and other international agencies to study the cost reduction and energy penalty issues under the specific conditions of the demonstration project. • Establishment of a standard mechanism and long term program to train its technicians and engineers • Cooperate/associate with some petroleum extraction companies to simplify storage research

Table 34 Institutional recommendations to enhance the financing capacity

Current conditions	International position	Gaps analysis	Recommendations
• Government policy to spur on CCS projects is not yet in place. • No funding support for CCS project	• Funding Mechanisms under the UNFCCC - GEF - LDC - Special Climate Change Fund	• No supporting government policies currently • No engineering funding support	• Need Chinese government to provide favorable supporting policy such as feed in tariff to compensate the

development at present. • Some cooperative research on CCS technologies has been undertaken using the international fund.	- Adaptation Fund • Funding Mechanisms outside the UNFCCC - SCF - CTF - FCPF - CPF - CBFF - SPA - Scaling-up Renewable Energy - UN-REDD Program - MDG Achievement Fund - EU-Global Climate Change Alliance - Cool Earth Initiative - Environmental Transformation Fund - International Climate Initiative - International Forest Carbon Initiative • regulatory policy such as GHG emission cap and trade	• No engineering funding support to gain practical experience in China	high investment and operation cost • Cooperate with developed countries and try to get free financial and technology transfer • Make use of the every possible advanced technology to reduce its construction and operation cost • GreenGen company should set up a special department to do research on the regulations of various relevant international funds and to explore potential possibility to use the existing international funds

Table 35 Institutional recommendations to enhance administration capacity

Current conditions	International position	Gaps	Recommendations
• Full experience in normal coal fired power projects in: • Project preparation and pre-construction • Project construction • Project pre-operation • Project operation	• Strong technical background in all CCS processes • Long time relevant engineering experience • Several CCS demonstration scale projects	• Technical background in CCS is not strong • Limited knowledge in CCS engineering processes • No engineering experience • No CCS demonstration projects in China	• Chinese government shall establish a powerful agency composed by different key stakeholders to coordinate the whole chain of CCS. • GreenGen shall set up an inner special dept. for the department for the coordination. • Cooperate with national and international research agencies to master advanced engineering management and O&M knowledge and experience in CCS. • Study and adopt existing international CCS demo project experiences • Adjust GreenGen's management mechanism/structure in conjunction with CCS

engineering process.

14. RECOMMENDATIONS AND CONCLUSIONS

Following conclusions from this project can be drawn:

1. Carbon capture and storage (CCS) is one of the important options to reduce cost for greenhouse gas mitigation in the future energy development in China. For CCS development in China, more demonstration proofs are needed to convince the general public and the public/private sectors that CCS is a viable option in dealing with carbon emissions issues.

2. An CCS project roadmap was developed in this project as a first order guideline. The implementation of CCS demonstration projects can be divided into seven phases. The guideline includes a comprehensive list of key working activities, to provide operators of CCS demonstration projects in China with a realistic and beneficial checklist from which to begin taking actions.

3. Since investment in a CCS demonstration project is financially unviable in the current situation, there needs to be some kind of government incentive to encourage motivation. There are essentially three policy tools that the government can use to assure the required return on investment in CCS related projects in order to trigger off CCS demonstration and deployment in China, i.e., manipulation of the electricity tariff, subsidization of capital cost and exemption of the income tax. More financial tools can be further developed, for example, the use of CDM for CCS if that could be agreed internationally or various carbon intensity targets. How all the incentives are going to affect a CCS project depends on an optimal mixture of the various approaches in consideration of balancing different factors.

4. Multiple entities with complementary expertise should join efforts in order to manage the full CCS chain for demonstration projects. The early commercial projects have combined the expertise of multiple stakeholders and thereby distributed risk because each partner has something specific to offer. Individual enterprises lack the comprehensive knowledge and technical capacity to conduct a fully integrated CCS project. The project will require a multitude of actions to be carried out by a diverse

group of stakeholders including many functional branches of government in order to implement the full project.

5. An integrated gasification combined cycle (IGCC) with CCS has feature for the reduction of cost and energy penalty compared with a pulverized coal power plant with CCS when the installation capacity is increased. Further development of various CCS technologies through learning by doing will offer more opportunities for the cost reduction.

6. The equipment manufacture and localization are the key factors for the cost reduction of IGCC with CCS as well as other CCS technologies. Gasification unit and gas turbine are the top two units in terms of localization potential, and their contributions account for 80–90% in the whole cost reduction of IGCC resulted from localization.

7. Methodology for assessment of CO2 geological storage in reservoir and saline aquifer of Dagang Oilfield complex have established including the properties of the geological storage, depth, fault sealing, exploration degree, rock properties and sealing， etc.

8. According to the geological analysis carried out for the Dagang oil field complex for this project, there are six sites suitable for CO_2-EOR based on published data. Miscible and Immiscible CO_2 flooding would be required for CO_2-EOR. During CO_2-EOR, CO_2 would effectively stored underground. Following CO_2-EOR, the depleted oilfield could also be used for storage. Saline aquifers near these oil fields were also considered for storage which is considerably larger storage potential (an estimated 38 – 55 Mt based on irreducible water saturation between 10 to 40 %). From the view point of source-sink matching, CO_2 emitted from IGCC could be stored for 30-50 years in the assessed fields. The distance between Greengen phase I of the IGCC power plant and the assessed sites is 100 to 150 km.

9. The main bottleneck in conducting an integrated CCS demonstration lies in identifying an appropriate storage site. The primary necessity for any CCS project is identifying a suitable storage site, whether for saline aquifer storage or EOR. Characterization of the proposed storage site is the most important step to enable a CCS project to be operated safely and successfully. While site characterization begins in the early stages of a CCS project, international experience shows that it is an iterative process requiring not only time to collect, process, and model subsurface data but also special technical expertise in various sub-specialties of geology, reservoir engineering, well drilling, and more.

10. There are a series of technical, institutional, legal, regulatory, and financial gaps to be filled either before the demonstration project or in the process of implementation. Chief among these are proving reliable and continuous operation of the IGCC plant itself, developing adequate skills in storage site characterization, classifying CO_2 as a substance and establishing basic regulations for its capture, transport, and storage and determining the long-term management plan of the storage site.

12. From the SWOC analysis, the following findings have been identified at both the national and project level. At the national level, both challenges and opportunities exist for CCS in China as an option to reduce its growing GHGs emissions. Opportunities mainly come from three aspects: CCS as a new option for China's CO_2 mitigation technology toolbox, as a major CER supplier in international market; and as an important opportunity for involvement within international technology research and development. Challenges mainly come from the following aspects: failure of a comprehensive international agreement; contraction of the international carbon market due to cessation of second commitment period of Annex I countries; and competition with other mitigation options. At the project level, the scale of a CCS demonstration project and transportation options are largely determined by the scale of selection of storage site and ways of utilization of captured carbon dioxide. The CCS value chain should be regarded in an integrated manner where strength, weakness, opportunities and constrains should be considered as a whole.

Main recommendations can be given as follows:

- China needs to conduct one or more integrated CCS project in order to master this strategic technology. An IGCC-CCS demonstration ought to be one of the earliest starting choices. The scale of CO_2 capture and storage should be large enough to achieve relevant experience. The project suggests the planned IGCC-CCS demonstration be about 1 Mt per year.

- It is strongly recommended that an electricity tariff of RMB 0.56/kWh, which was theoretically applied to the Greengen Phase 1, remains as the lowest level of electricity tariff to CCS related power plants. Under this circumstance the best economic situation of course is that the demonstration project can sell its captured CO_2 to an oil field for EOR. The price of CO_2 could be less than $10 per tonne. However, this approach is

unsatisfactory in the sense of full carbon storage. An optimal choice would be that the government raises the tariff by 20-30% from the current IGCC tariff, with the aim to cover the energy penalty caused by CCS. Meanwhile, the project also gets grant financing from international climate change related funds to subsidize the additional part of the initial capital cost. Tax exemption or tax reduction during the operation, if properly conducted, shall further facilitate mitigation of the financial burden.

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

- China should act quickly in establishing the comprehensive capacity to conduct site characterization and storage operations and in identifying appropriate storage sites. There is an urgent need to identify appropriate storage sites as soon as possible because site characterization is very time intensive and positive results are not guaranteed. China currently has related specialists scattered across different sectors, but to be efficient in site characterization, China should organize its experts and foster specific capability in site characterization, especially in developing capabilities for subsurface geology and CO_2 plume modelling and monitoring. Because geological information for many regions of China is sparse, initial CCS demonstration projects should limit their search of a storage site to locations with good, pre-existing information in order to cut costs and save time. For GreenGen project, one of the fields in Dagang complex (Storage site E) is considered as a suitable storage site based on the location, storage potential, population density, local infrastructure and other parameters. More geological and geophysical data are necessary for more detailed study. Other candidates of storage sites could also be considered for the further investigation such as the nearby Huabei, Shengli and Liaohe Oilfields.

- The specifications for the first IGCC-CCS demonstration project recommended by project

are: (1) The plant should be designed with the freedom to be either a pure IGCC plant or IGCC plant with polygeneration; (2) A capture rate of at least 60% with the ability to reach 90% as necessary to realize the megaton-scale capture objective but not overburden plant operation costs; (3) CO_2 should be transported from the IGCC plant to the storage site via CO_2-specific pipelines; (4) CO_2 handling facilities and pipelines should be designed to handle a flexible range of impurities. Special attention for R&D should be paid to location of key equipments including gasification, CO_2 separation and gas turbine, whose cost may cut down significantly. Meanwhile, the policies specific for promoting the technology transfer, independently develop, and technology demonstration should be issued, which will finally drive the decarburization of coal relied power industry of China.

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

The following future work shall be considered:

1. Locate the break point for early CCS demo in China.

- The priority section and area for early CCS demo in China should be indicated and recommended to the central government. Comparing the techno-economic performance of CCS technologies in different section (chemical, power or coal-liqufication) and area (western or eastern area, etc.), and locate the priority options for early CCS demonstration.

2. Supporting GreenGen CCS pilot plant (IGCC with pre-combustion capture)

- Techno-economic analysis and comparison of optional case for pilot plant (60,000 tone CO_2 treatment capacity per year): As the first engineering effort for pre-combustion capture technology in China, the pilot plant of GreenGen will be the key step toward the dissemination. In depth survey and analysis of the related projects in the world will be conducted for supporting the GreenGen pilot plant. Technical and financial solutions for the pilot plant will be investigated in details, which is important for the decision maker.

- Technical solution to reduce the energy penalty in CO_2 capture: studies shall be conducted on various technical options to reduce the energy penalty associated with CO_2 capture including for example, thermal integration or new CO_2 separation technology, for GreenGen.
- Integrated method for the whole CCS chain including capture, transport and storage: Integrated complex among the CCS chain will significantly affect the performance of the CCS. Impacts on CCS will be investigated and optimized not only in each process but also the whole chain.

3. Technical-economic solution for storage in CCS pilot project

- The technical-economic solution for storage in GreenGen CCS pilot project: The storage technology is the key process for the successful implementation of whole CCS chain. Further investigation of the geological information of candidate sites near to the pilot IGCC plant will be conducted including assessment of adaptability to the CO_2 resource, identification of oil well suitable for EOR and storage, monitoring methodology etc.
- The mechanism involving the key stakeholders (especially oil and gas sector) into cooperation: How to involve the key stakeholders into cooperation is one of the key problems concerning the implementation agency. This work will evaluate the acceptance to pilot project of each key stakeholders, identify the crucial gap blocking the cooperation, and recommend the mechanism (economic or policy) to build the effective cooperation.

4. Investigation the economic incentives on CCS

- In-depth analysis of the detailed engineering possibilities to lower the manufacturing and O&M of the whole CCS chain with special considerations of China’s conditions shall be further conducted. It is recommended to address this issue by applying a real engineering application.
- Putting a Price on Carbon will benefit CCS development, but so far there is lack of detailed analysis on carbon pricing, and impact on CCS. Therefore study on carbon pricing, carbon tax, and impact of carbon pricing and tax on CCS development is needed.
- Mandating GHG Emission Rates could provide essential environment for CCS deployment.

There is no total emission target so far in China. However we do see the possibility for some province and cities to take total amount control target for energy and carbon. Further study is needed to analysis the possibility for emission control target and impact on CCS development.

- In the combination with the existing funding mechanism, new financial instruments including international emission trading schemes shall be studied for the possibility to apply for CCS implementation and demonstration in China.