CCS challenges and opportunities for China

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Abstract

CCS is a R&D priority for China, covering all capture options, transport and storage, together with a strong level of international co-operation. With regard to progression beyond research, there are some very significant large industrial scale trials that are being funded and implemented by various Chinese power generation, coal and oil companies. As well as part CO_2 capture from coal fired power plants, these include a full chain CCS trial on a coal to synthetic oil unit, which comprises part capture of the CO_2 vented from the coal gasifiers together with subsequent transport and storage in an aquifer. There are also various CO_2 enhanced oil recovery activities underway, reflecting China's interest in CO_2 utilisation. From a technical perspective, China is well positioned to move forward from these trials towards demonstrations of various CO_2 capture and utilisation/storage options. However, this will require the global CCS community to fully engage with China as to how these projects can be best financed and how (and to what level) the information arising can be disseminated to aid complementary projects elsewhere. While the primary focus will be on the power sector, the prospect of establishing CCS on clusters of coal to chemicals gasification units in certain regions of China offers some early, lower cost opportunities for demonstration. Details, including likely CO_2 emission levels, on the modern, oxygen blown gasification units that are either operational or at the contracted design/construction stage in China are included within an extensive annex to this report. At the same time, China might benefit from further assistance with regard to characterisation of nationwide CO_2 storage opportunities and in establishing regulations to ensure that large-scale commercial initiatives do not compromise health, safety, and the environment.

Acronyms and abbreviations

kW	kilowatt
m^3	cubic metre
ppm	parts per million
t	tonne
CAS	Chinese Academy of Sciences
CBM	coalbed methane
CCS	carbon capture & storage
CDM	clean development mechanism
CHP	combined heat & power
CO	carbon monoxide
CO_2	carbon dioxide
CPIC	China Power Investment Corporation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSLF	Carbon Sequestration Leadership Forum
CTL	coal-to-liquids
EC	European Commission
ECBM	enhanced coalbed methane
EIA	Energy Information Administration
EOR	enhanced oil recovery
EU	European Union
FGD	flue gas desulphurisation
FYP	Five-Year Plan
GDP	gross domestic product
GHG	greenhouse gas
GJ	gigajoule
GWe	gigawatts electric
Gt	gigatonnes
H_2	hydrogen
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IT	information technology
LBNL	Lawrence Berkeley National Laboratory
MEA	monoethanolamine
MOST	Ministry of Science & Technology
MoU	memorandum of understanding
MPa	mega pascal
MWe	megawatt electric
Mt	million tonnes
NDRC	National Development & Reform Commission
NEA	National Energy Agency
m^3/h	cubic metres per hour
NOx	nitrogen oxides ($NO + NO_2$)
N_2	nitrogen
O_2	oxygen
OECD	Organisation for Economic Cooperation & Development
OOIP	overall oil in place
PC	pulverised coal
R&D	research & development
RD&D	research, development & demonstration
RMB	Reminbi

S&T	science & technology
SC	supercritical
SEI	strategic energy initiative
SO_2	sulphur dioxide
TPRI	Thermal Power Research Institute
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USA	United States of America
USC	ultrasupercritical
US$	United States dollar

Currency converter

All costs quoted in this report are given in the units used in the original references. These are either the Reminbi (RMB), China's currency, which has been used in various Chinese estimates of equipment costs, or US dollars (US$), which have been used where such estimates have been attributed to, say, an international technology supplier. These data can be several years old. The exchange rate as of June 2011 was 6.5 RMB:1 US$. However, caution must be used as while the RMB: US$ exchange rate was traditionally constant, it has changed significantly since the onset of the global financial crisis.

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1 Introduction

1.1 Background

China is making considerable progress to reduce both its national energy and carbon dioxide (CO_2) intensity levels, particularly in the power generation sector. This has included the successful and ongoing introduction of a significant amount of low- and zero-carbon power generation capacity, including hydro, wind, nuclear, solar and some natural gas. China has also implemented an ongoing improvement programme, through the extensive introduction of modern coal-fired plant with increasingly higher energy efficiency and environmental performance (Minchener, 2010). While all of these approaches will reduce CO_2 emissions, there are limits as to what can be achieved in the near to medium term because coal-fired power generation will continue to dominate the power sector in a growing economy for decades to come. Consequently there is significant interest with regard to additional steps that might be taken to further tackle greenhouse gas (GHG) emissions, especially arising from the use of coal. This includes technologies that could significantly reduce CO_2 emissions in absolute terms.

Carbon capture and storage (CCS) is one of a number of measures that could help to significantly reduce CO_2 emissions (IEA 2009a,b; 2010a). However, it is not yet a commercially available technology although there is considerable research, development and demonstration under way, particularly in Europe, North America, Australia, Japan and now China. The research and development (R&D) is focused on reducing the costs and improving the efficiency of capture technologies as well as addressing key issues such as mapping the CO_2 storage capacities in numerous countries and developing monitoring and verification techniques for safe overall operation. Alongside the technical activities, several countries are addressing the legal, financial and policy issues such that large-scale projects can be established and regulations can be put in place to ensure the long-term safety of CO_2 storage.

It is evident that the major coal-using nations must all be engaged in this global initiative if it is to be successful. In this regard, it is important to recognise that China has increasingly become an active participant in various international climate change initiatives, while also pursuing various activities on its own. These include CCS, covering both the technical and economic challenges and the need to address legal and regulatory barriers.

1.2 Structure of the report

This report provides a review of China's CCS related research, development and demonstration ambitions and activities, which is structured as follows. An overview of the various technological options for CCS is presented, including their current global development status and demonstration needs. This is followed by a review of China's policy initiatives that relate to climate change and possible mitigation approaches based on its own national conditions. This includes the framework within which such initiatives are established and implemented, together with a focus on coal-fired power generation and other energy intensive sectors. To put the need for such work in context, there follows a description of the current contributions to China's CO_2 emissions from coal, including power generation, non-power gasification processes, coking and the steel sector, and various other industrial processes. Projections for future CO_2 emission levels under a number of scenarios are considered and comment is made about the potential role for CCS, including in which sectors it might best be applied.

An overview of China's extensive CCS research and development (R&D) programmes, including the scope of the activities as well as the various funding sources, is then provided. The capture activities cover both improvements to the nearer-term options and also the establishment of the so-called second generation technologies, which are less well developed. This work is complemented by a combination of fundamental and small-scale practical studies examining the various CO_2 storage options, with emphasis on the nearer-term prospects for CO_2 based enhanced oil recovery (EOR) as CO_2 utilisation is an integral part of China's R&D programme.

This is followed by a description of the associated CO_2 EOR and storage trials being undertaken by Chinese industrial enterprises, all of which link back to the R&D activities described previously. For completeness, some self-contained CO_2 utilisation trials are also mentioned.

The extensive CCS initiatives within China's coal power generation sector are then described. This includes the various ongoing and planned large industrial scale CO_2 capture and utilisation activities for pulverised coal (PC) based combustion plant. This is followed with an update on China's activities to demonstrate its own integrated gasification combined cycle (IGCC) technology to which pre-combustion CO_2 capture is likely to be added in due course, subject to successful operation of the gasification-based power generation system. With regard to utilisation, the focus is on using the CO_2 for a range of industrial applications, including the food and beverage sectors as well as EOR.

Consideration is next given to the rapidly growing number of large-scale modern coal gasification plants for non-power applications that are being deployed, which represent a potentially attractive early opportunity for the application of CCS and EOR, especially through clustering of various units in specific industrial locations. This is because an inherent characteristic of the coal gasification process of such plants is that large quantities of high concentration CO_2 are separated and, at present, vented into the atmosphere. Consequently, the marginal costs for the application of CCS to such plants would be much lower than for coal-based power generation processes, since it would only be necessary to provide for compression, transport and injection of CO_2 into suitable storage sites. A description is included of China's first integrated industrial-scale CCS project, which has been implemented on the country's direct coal to synthetic oil demonstration plant and includes CO_2 storage in an aquifer. This chapter is supported by the inclusion of an extensive annex that provides data, including likely CO_2 emission levels, for the modern, oxygen blown coal gasification units that are either operational or at the contracted design/ construction stage.

The relative importance of CCS international co-operation ventures for many of the types of projects described previously, are then considered, including the overall framework and rationale behind the various agreements. Finally, comment is made on the likely impact, both internally and on an international basis, arising from China's current activities and possible future plans.

2 Overview of the CCS process

The CCS process comprises three integrated stages, namely:
1 capture and subsequent compression of the CO_2;
2 the transport of the CO_2 in a supercritical/dense phase;
3 its subsequent injection into the selected geological formation.

The choice of capture technique depends on the type of industrial process, from which the downstream transport and storage stages are essentially independent. All CCS options incur costs and reduce the efficiency of the plant. Fitting CCS to a power plant requires additional capital investment for the CO_2 capture and compression equipment, the transport infrastructure as well as the equipment associated with the storage activities. In all cases, CO_2 capture will use additional energy for the capture and subsequent compression of the CO_2 that will reduce the overall process efficiency and also increase the amount of fuel used to achieve a given power generation output. Consequently, the cost of capturing CO_2 will be lowest if this is done in large plants, in gas streams having a high concentration of CO_2 and which are at elevated pressure.

Capital costs are expected to reduce once this technology is demonstrated and then deployed on a significant scale. Improvements in the efficiency of the capture technologies and effective integration with the other process components will lead to reductions in the energy penalty. At the same time, other aspects such as the reliability of the plant, scalability of the equipment, maintainability, as well as consumption of water will need to be considered. The cost of CCS will also be affected by the length of pipeline between the power plant and the storage site, as well as the type and depth of storage. Offshore storage would be more expensive than onshore storage (Freund, 2009).

2.1 Carbon dioxide capture and compression

The various different ways to capture CO_2 in large industrial processes are typically categorised as first and second generation processes. The former are reasonably well understood but have yet to be applied on a large scale, and include post-combustion, pre-combustion and oxyfuel combustion.

Post-combustion capture systems separate CO_2 from the flue gases produced by the combustion of the fuel in air (Figure 1). At present, separation would typically be by use of a liquid solvent, of which monoethanolamine (MEA) is the industry standard although more effective options continue to be developed and established. Areas for development include better integration of the combustion process with the CO_2 capture stage in order to minimise efficiency losses and potential plant flexibility/availability problems. This technology could be used in either new or existing power plants (or other large industrial processes) although to date there have been no full-size applications of CO_2 capture at large (for example 500 MWe) power plants. Processes using ammonia solvents are under development and may reach the market in the medium term. There is also work under way to avoid solvent-based systems through the use of either membranes or solid sorbents, both of which are at a very early stage of development (NZEC, 2009a).

With pre-combustion capture systems, the primary fuel is first reacted in a vessel with steam and oxygen under reducing conditions to produce a synthesis gas, consisting mainly of carbon monoxide and hydrogen (*see* Figure 2). This gas mixture is then passed with steam over a catalyst in a second reactor (a 'shift reactor') where the carbon monoxide is converted into CO_2 and additional hydrogen. The resulting mixture of hydrogen and CO_2 can subsequently be split into separate streams using a physical solvent process (for example Selexol or Rectisol). For the power sector, pre-combustion capture would most likely be used on coal-power plants based on IGCC technology. The techniques that would be used for pre-combustion capture are already in use on coal gasification plants for the

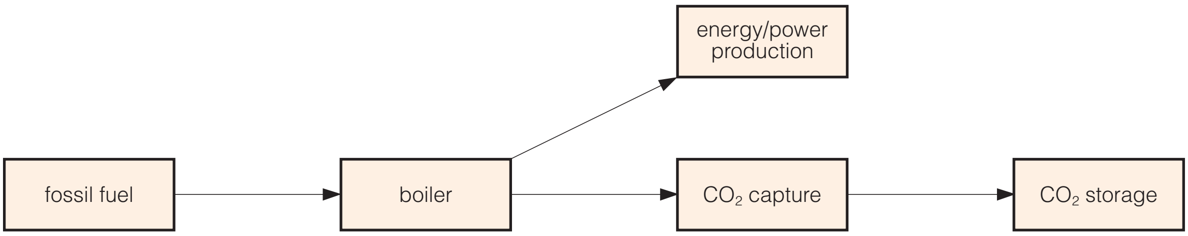

Figure 1 Post-combustion capture of CO_2 (NZEC, 2009a)

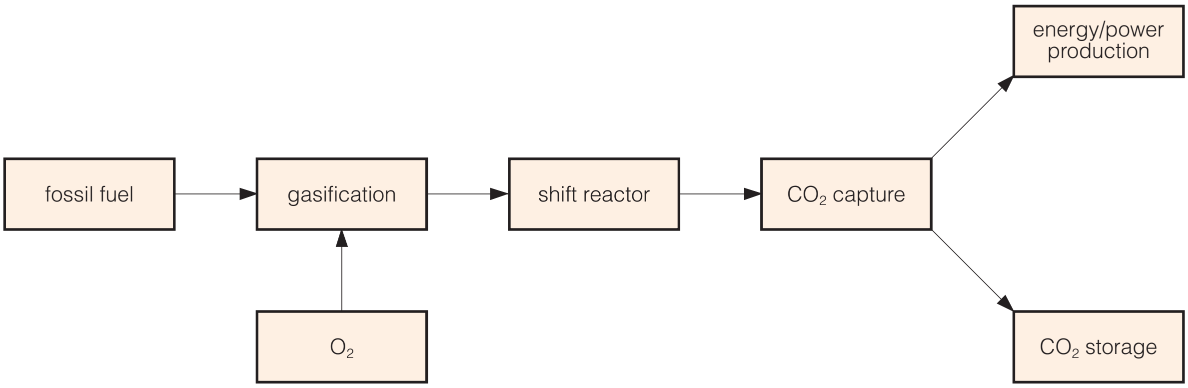

Figure 2 Pre-combustion capture of CO_2 (NZEC, 2009a)

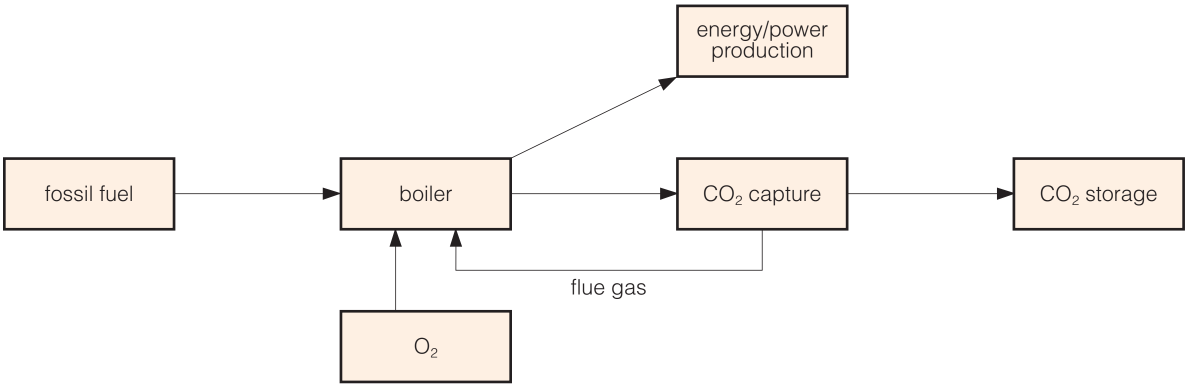

Figure 3 Oxyfuel combustion with capture of CO_2 (NZEC, 2009a)

large-scale production of hydrogen for ammonia and specialist chemicals manufacture, in petroleum refineries and coal-to-liquids plants (Minchener, 2011). As with post-combustion systems, the successful development of gas separation membranes, in this case as an alternative to cryogenic O_2/N_2 separation and H_2/CO_2 separation, would result in lower energy penalties.

Oxyfuel systems would use oxygen instead of air for combustion of the primary fuel to produce a flue gas comprising mainly CO_2 and water vapour (*see* Figure 3). The latter would then be removed by cooling and compressing the flue gas stream. However, further treatment of the flue gas would be needed to remove pollutants and non-condensable gases before the CO_2 would be of adequate quality to meet the transport pipeline specifications (Kunze and Spliethoff, 2011). This technology is currently at the pilot-scale development stage (Davidson and Santos, 2010).

There are also several promising CO_2 capture concepts (for example post-combustion carbonate looping, chemical looping combustion, membrane-based systems), which are being tested in laboratory prototype installations (Davidson, 2009; Henderson 2010). They are of interest because they have the potential to significantly reduce the energy penalties associated with the first generation processes. The development of these second generation concepts is progressing towards the pilot-scale stage when a robust assessment will be possible, after which the more promising options will be taken forward for large-scale trials.

The expectation is that all these CO_2 capture processes would be used at large-scale stationary CO_2 point sources such as power stations and energy-intensive industrial processes. Under such conditions, irrespective of which technology might be used, large amounts of CO_2 would be captured and so it would be impractical to move these long distances as a gas. Therefore the expectation is that the CO_2 would be compressed close to or above its critical pressure of 7.4 MPa, where many of its properties are similar to that of a liquid. In this state it is often referred to as a dense phase fluid. If it is above its critical pressure and its critical temperature of 31.04°C it is referred to as supercritical fluid. Compression to a dense phase or supercritical fluid makes transport of CO_2 easier and less costly.

2.2 Transport of carbon dioxide

For the scale of operation envisaged with capture of CO_2 from, say, large coal-fired power plants at an onshore location, the most likely transport option is by pipeline. For smaller-scale applications, such as tens to hundreds of tonnes per day from capture on a demonstration project, road tankers may be the more suitable means of transport. Should there be a need for CO_2 transport from the coast to an offshore storage location, either pipelines or large ocean tankers would be suitable. Sea transport would most likely to lead to the requirement for pressurised or semi-refrigerated storage of large quantities of CO_2 at or near the docks (NZEC, 2009a). Although CO_2 has been transported in a dense or supercritical phase for various applications (Orr and Taber, 1984), the peculiar properties of compressed CO_2 present one of the main challenges to CCS technology. Health and safety issues related to pipeline transport include design, integrity assessment, leakage and dispersion modelling.

2.3 Carbon dioxide storage

Geological storage of CO_2 is considered the most technically and economically viable option, for which three main characteristics are normally considered: the capacity to hold CO_2; whether it can retain the CO_2 safely and securely; and how easy it would be to inject CO_2 into the formation. For reservoirs that have previously held hydrocarbons for millions of years and have potential for storage of CO_2, this will depend in part on how the hydrocarbons were extracted as the existence of a large number of wells, for example, might involve extensive remedial work to ensure the long-term containment of CO_2.

There is also potential to inject CO_2 into mature oilfields to improve the recovery of oil through EOR, although the economics of this process can be quite variable as they depend on the price of oil, the cost of CO_2, and the location of the reservoir in relation to the CO_2 source. There is much experience with large-scale EOR, mainly in the USA (Carter, 2011).

Saline aquifers are likely to have the greatest potential for storage of CO_2 globally. Such aquifers are filled with salt water and typically have no commercial use at present. Consequently, as yet, there is limited information available on their characteristics although this is being gained via large-scale projects in several countries (NZEC, 2009a). For this reason, estimates of storage capacity of aquifers must at present often be based on gross assumptions extrapolated across large areas rather than more detailed, site-specific assessments (Kuuskraa, 2004). This is in contrast to, say, possible EOR operations where estimating the potential capacity for CO_2 storage is aided by the availability of geological information in the public domain.

pressure would be high enough for the CO_2 to be almost as dense as liquid water. The reservoir rocks need to be porous, so as to store large volumes of CO_2, and permeable enough to allow the easy flow of fluids but be capped by impermeable rock above to prevent escape of CO_2.

It may also be possible to store CO_2 and enhance the recovery of coalbed methane (CBM) by injecting it into unmineable coal seams although this has not yet been technically or economically proven. Other methods such as storage as a solid carbonate deposit have been suggested: however, these have not yet been established at any significant scale.

3 Policy issues

There are various government bodies that have key roles relating to energy sector policy issues (Minchener, 2010). The National Development and Reform Commission (NDRC) is responsible for overall policy/long-term planning and overall management in all the industrial sectors, which includes the development plans within the National Five Year Plans (NDRC, 2011a). In addition, there is the National Energy Administration (NEA), which has specific responsibilities for the energy sectors (NDRC, 2011b). This was established in 2008, as part of a move to strengthen the centralised management of energy sectors and deal with the major energy issues, within the NDRC framework of ensuring the sustainable and steady development of the national economy. The Ministry of Science and Technology (MOST) has responsibility for RD&D, and in the context of coal this covers all market sectors but with an emphasis on the power sector and the establishment of advanced technology (MOST, 2011a). The remit of the Ministry of Environmental Protection (MEP) includes the prevention and control of environmental pollution, and the safeguard of public health and environmental safety. Within the context of coal-fired power generation, the Ministry establishes environmental standards and emissions limits (MEP, 2011).

In January 2010, in recognition that energy sector management was spread between various agencies, the National Energy Commission was established with the remit to co-ordinate national energy development strategy, address significant issues concerning energy security and energy development, and co-ordinate major programmes of domestic energy development and global co-operation. The Commission is led by the Chinese premier with senior representation from all the other energy-related commissions and ministries (People's Daily Online, 2010a).

The State Council is both the senior administration and executive body within the State. It comprises the premier, vice-premiers, State councillors, ministers in charge of ministries and commissions, the auditor-general and the secretary-general (People's Daily Online, 2011).

3.1 China's energy and environmental initiatives

China operates on the basis of a five-year planning cycle, as defined by the Five Year-Plan for National Economic and Social Development. This sets out the intended way forward for the nation and provides guidelines, policy frameworks, and targets for policy-makers at all levels of government (APCO, 2010).

Each plan provides top down overall objectives and goals related to economic growth and industrial planning in key sectors and regions, while more recently also covering social issues. Although the timescale is nominally five years, many policies and directives flow through from one plan to the next. The process begins with State Government guidelines and supporting policies together with targeted policy initiatives, which are prepared by various national commissions and ministries. These then form the framework against which provincial and local organisations provide detailed work plans for achieving the designated targets.

There is also an ongoing process of review and revision over the five-year lifetime of the plan, not least because effective implementation can be difficult. The success of the top-down approach will ultimately depend on the definition and implementation of local level initiatives (APCO, 2010).

3.2 Historical review of the eleventh Five-Year Plan

The first ten FYPs were very much focused on economic issues. In contrast, the eleventh Five-Year

Plan was, in overall terms, a guidance document to shape the future direction of the nation. It included policy guidelines that addressed both near-term problems and longer-term needs. As such, it provided a vision and addressed issues that go well beyond the 2006-10 period, with considerable emphasis on the need for balance. It indicated that the Chinese Government recognised the importance of climate change issues, which was reflected in the policies and actions that were established (Zhong, 2010). Within this context, the Chinese Government focused on three major energy challenges: long-term energy security, limiting local environmental impacts and addressing global environmental issues. It committed to a major shift in the development pattern from being resource intensive towards resource sustainable, with an emphasis on efficiency, resource conservation and environment (NDRC, 2006).

Key targets were to reduce energy intensity and to control GHG emissions, for which enabling actions included:
- the establishment by the State Council of a National Leading Group to address climate change, energy conservation and pollutant discharge reduction;
- the launch of the Middle and Long Term Programme of Renewable Energy Development;
- the introduction of the General Work Plan, with appropriate public action, for energy conservation and pollutant discharge reduction;
- the declaration that the nation will achieve a 20% reduction in energy consumption per unit of GDP and 10% reduction of major pollutant (sulphur dioxide) discharge during the five-year lifetime of the plan.

The latter action was particularly significant, with the NDRC deciding how these two targets would be achieved between individual provinces and within the various industrial sectors (NDRC, 2006). Considerable emphasis was put on the improvement of coal power plant efficiency through the introduction of advanced high-efficiency units and the closure of small inefficient power plants (Minchener, 2010), together with the shut-down of obsolete, small steel-making and cement production units (NDRC, 2007a,b). For pollutant discharge reductions, this was addressed through the very extensive introduction of flue gas desulphurisation (FGD) for sulphur dioxide (SO_2) control on the remaining and all new power plants (Minchener, 2010). The latter target was met comfortably. However, for the energy reduction target, this was not quite met by the end of 2010, despite short-term rapid actions by officials in certain provinces during the final few months, including temporary closure of numerous industrial production processes (State Grid Corporation of China, 2010; Platts, 2011). Table 1 shows the overall achievement on a year-by-year basis.

Table 1 China's energy intensity change, 2005-10 (Li, 2011)

Year	2005	2006	2007	2008	2009	2010
Energy intensity cumulative change on 2005 level, %	–	3.13	7.81	12.50	15.63	19.10

3.3 Overview of the twelfth Five-Year Plan

The guidelines for the twelfth Five-Year Plan were approved by the Central Committee of the Communist Party of China during October 2010 while the National Peoples' Congress ratified and published the plan's outline approach in March 2011. This plan represents a continuation of broad policy direction and its key themes are rebalancing the economy, addressing social inequality and protecting the environment (China Daily, 2011a,b). From an economic perspective, a notional GDP annual growth rate target of 7% is assumed, with a greater emphasis on consumption-led inclusive growth rather than investments and exports (GCCSI, 2011).

For the first time, the Plan gives a high profile to climate change and environmental issues as well as to energy (The Climate Group, 2011). There are details regarding China's commitment to international co-operation and the UN-led climate negotiation process, including concerns about climate finance and technology transfer (WRI, 2011). The Plan also discusses the need to implement more climate adaptation-related policies. This reflects the fact that meeting China's increasing energy demand, while simultaneously reducing pollution and ensuring a stable, reliable and clean energy supply, has become an ongoing priority of the government. It is also backed up by a significant investment commitment. During the eleventh Five-Year Plan the government allocated RMB200 billion for energy efficiency and environmental protection measures, which is understood to have created a large knock-on effect of generating an additional RMB2 trillion in economic activity. For the twelfth Five-Year Plan period, it is understood that China's investment in the environmental protection industry will exceed RMB3 trillion, with the industry growing by 15–20%/y.

Within this framework, the intention is to develop seven strategic emerging industries (SEIs), which are in sectors where Chinese enterprises are expected to succeed on a global scale. These are biotechnology, new energy, high-end equipment manufacturing, energy conservation and environmental protection, clean-energy vehicles, new materials, and next-generation IT. The state government will steer the development of these industries by establishing industrial standards and supporting the entry of the main products to the international market (Global Times, 2010). This will include facilitating co-ordinated development together with support for regional distribution. In addition, it is understood that the government intends to increase the SEIs' contribution to GDP from approximately 5% in 2010 to 8% by 2015 and to 15% by 2020 (APCO, 2010).

In terms of energy sources, the intention is to continue to mitigate GHG emissions by accelerating the transformation of the country's economic development pattern (China Daily, 2011a). Several important energy and environment targets have been set for the period to 2015, with:

- energy consumption per unit of GDP to be cut by 16% from 2010 levels;
- SO_2 and nitrogen oxides (NOx) emissions to be cut by 8% and 10% respectively from 2010 levels;
- CO_2 emissions per unit of GDP to be cut by 17% from 2010 levels;
- non-fossil fuel use to account for 11.4% of primary energy consumption;
- expenditure on research and development to account for 2.2% GDP, with an emphasis on scientific and technological innovation leading to Chinese intellectual property rights;
- water consumption per unit of value-added industrial output to be cut by 30%.

China comprises a very large land area and there are considerable geographical differences in the levels of industrial development. The major centres of population are in the eastern and south-eastern provinces where the majority of commercial and industrial production processes is located. For example, there are nine key economic regions, which are the three major economic zones around the cities of Beijing, Shanghai (Yangtze River Delta) and Guangzhou (Pearl River Delta, Guangdong Province), together with six areas around the cities of Shenyang (Liaoning Province), Changsha (Hunan Province), Wuhan (Hubei Province), Chongqing-Chengdu (Sichuan Province), the Shandong peninsula, and the coastal area west of the Taiwan strait (China FAQs, 2011). These regions, Figure 4, comprise the population and economic centres of the country. They account for 64% of national GDP, 43% of total energy use, and 39% of the population. With the exception of Chongqing-Chengdu, all are located on the eastern and south-eastern side of the country. Consequently, the energy and environment initiatives take into account these regional economic differences such that the more developed provinces will be expected to show greater improvements than the others.

Thus, with regard to the energy-intensity targets, the intended 16% overall cut in energy consumed per unit of GDP is the national target. The overall savings requirements will be allocated amongst the provinces in a predominantly top-down process, as was undertaken during the previous five-year period (Chinadialogue, 2011a), taking account of local circumstances, especially the level of development. The eastern and central provinces have been allocated targets in the range 16–18%.In contrast, the western provinces, Qinghai, Xinjiang and Tibet, Figure 4, which are relatively undeveloped and have large ethnic minority populations, were given energy-intensity targets of 10%,

Figure 4 Schematic map of the provinces of China (Muztagh, 2011)

while Ningxia and Gansu, also in the west, were given 15%. Performance against these will be reviewed at the mid-point of the Plan and can be adjusted by the NDRC, depending on progress to date and scope for improvement.

The CO_2 emissions target is in line with China's pledge to achieve a 40–45% reduction in carbon intensity per unit of GDP from 2005 levels that was first announced in 2009, with the focus to be on high-polluting and high-energy usage sectors (State Grid Corporation of China, 2010), The Green Leap Forward, 2009). In order to meet that commitment, government officials have recently made statements that a carbon tax may be implemented by 2013, as well as some type of carbon trading system by 2015 (China Daily, 2010). It is also important to note that China has stated its intention to establish statistical and monitoring systems for GHG emissions, energy conservation and emissions reductions to ensure that the various targets are tracked and properly implemented. At the same time, the rush for economic growth among local governments also poses challenges for China's environment. Consequently, local officials' performances will be reviewed for both the growth rate in their regions and their efforts to protect the environment and public health.

In the power generation sector, the Chinese Government announced plans to build 235 GWe of capacity for non-fossil energy sources in the next five years (People's Daily Online, 2010b). This will include:
- starting 40 GWe of nuclear power projects in the coastal areas and central regions;
- 120 GWe of hydropower stations;
- at least 70 GWe of wind power capacity with six large power bases to be located on land and another two in coastal areas;

- 5 GWe of solar power capacity, to be located in Tibet, Inner Mongolia, Ningxia, Gansu, Qinghai, Xinjiang and Yunnan (*see* Figure 4).

For coal-fired power generation, the current initiatives to improve overall energy efficiency will be continued while the expectation remains that coal-fired power will continue to show significant growth although not at the levels seen in the period 2006-10 (Minchener, 2010). It is expected that the annual increase in capacity will be some 50 GWe, all of which except for CHP schemes will be either 660 or 1000 MWe high efficiency supercritical and ultra-supercritical units. None of this will include CCS. Indeed, despite these very promising energy and environmental initiatives, there is no provision for CCS in the Plan and the official position remains that CCS technology is as yet unproven and too expensive for current deployment. However, it remains a development priority in energy R&D, as is considered in Chapter 5.

Alongside the continuing investment in new capacity, a key government priority is the further development of the country's power transmission system, with plans for the large-scale construction of a smart grid to begin during the twelfth Five-Year Plan period. The State Grid Corporation's expected investment level will be in excess of RMB 17 billion during this time (Metering China, 2010). The reform of electricity prices and systems is also included in the plan, which advocates making full use of the market in setting prices and implementing independent transmission prices.

For the coal-fired power generation sector, probably of greatest importance is the restructuring, which aims to integrate the coal and power sectors at giant coal-power bases (Rui and others, 2010). The problem to date has been that coal prices are market-based, but power prices are tightly controlled by the government. This caused massive losses for Chinese power generators in 2008 through 2010 and triggered government intervention in the coal market with attempts to cap the price of coal. At the same time the power companies made massive purchases of imported coal and not just for use in the coastal power plants. The Government's policy is to establish a limited number (~10) of coal-power bases to produce about half of China's coal requirements under the control of various state-owned enterprises and central government.

This move would increase control over the coal sector and over coal prices for a large share of the market within integrated state owned enterprises. This would represent a very meaningful shift in how coal is priced in China, possibly leading to a two-tiered pricing structure (Rui and others, 2010). It would also help bring about modernisation and mechanisation of a larger share of China's coal production, in theory bringing larger economies of scale to the sector. While up-front capital investment per tonne of coal produced would increase, the marginal cost of coal production should decrease. At the same time, for the last decade, the levels of imports have become very significant as they have become the balancing factor for China's coal production and utilisation, with a major impact on global traded coal prices. The development of coal-power bases could significantly alter coal price formation in China with a knock-on impact on imports.

From a technical perspective, there will be incentives for new coal-fuelled energy production to be located in the country's central and western provinces at these bases (Business China, 2010). The intention will be to establish numerous 'coal to wire' power generation projects, as well as coal transformation enterprises should the latter be deemed a sensible way forward by the NDRC although at present this is questionable given coal and water concerns for such projects (Minchener, 2011).

Finally, in terms of overall coal use, there have been public statements from officials suggesting that the Government will set an upper annual limit on total coal use within the duration of the twelfth Five-Year Plan, at 3.6 to 3.8 Gt for the period 2011-15. This compares with the 3.2 Gt used in 2010 (China Daily 2010; China.org, 2011).

3.4 CCS for China

With regard to the development and deployment of CCS to address certain climate change issues, the NDRC noted that there is a need for a range of comprehensive measures, to be adopted on an international basis (NDRC, 2007c). At the same time, further advances in science and technology are needed to establish some of the key means to limit GHG emissions. In this regard, China recognised that CCS is a leading-edge emerging technology with great CO_2 reduction potential and, as such, needs to be seriously considered by the international community. As a consequence, the following steps were taken to move CCS forward from a concept towards a viable technology.

The 'Outline of the National Programme for Medium- and Long-Term Science and Technology Development' was issued by the State Council in February 2006. This provided guidelines, objectives and the general framework for China's science and technology development for the following 15 years (MOST, 2007a,b). In particular, CCS was highlighted in the programme as an important but long term technology, while 'the development of efficient, clean and near-zero emissions fossil energy technology' was listed as a key component within the advanced energy area.

In June 2007, the State Council issued China's National Climate Change Programme*,* which set out the objectives, principles, priority areas and countermeasures, positions, and need for international co-operation to address climate change (NDRC, 2007c). This states that the strategic goal of China in order to respond to climate change includes making significant achievements in controlling GHG emissions, and that it will pursue a number of mitigation and adaptation approaches. This includes the need to develop CCS as one of the key means for GHG reduction.

These principles were developed further by MOST and thirteen other ministries and then published as a listing of Scientific and Technological Actions on Climate Change, later in June 2007. This document was intended to co-ordinate climate change-related scientific research and technological development. In terms of technological development for GHG emission controls and climate change mitigation (MOST, 2007b) this included:

- CO_2 capture, utilisation and storage technologies, namely through the development of key technologies and measures for capturing, utilising and storing CO_2;
- the design of a technology roadmap for CO_2 capture, utilisation and storage;
- the implementation of capacity building;
- the establishment of an engineering and technical demonstration project.

It is important to note that in China, before 2006, there was very little interest, even at the academic level, in CCS. However, since then, with the Government's inclusion of the technology within its strategic plans arising from the eleventh Five-Year Plan together with several capacity-building international co-operation actions, there has been an upsurge of technical interest and, as is reported below, with several relatively large-scale projects being established.

MOST is now developing an outline overall plan, which will define the objectives of CCS technology in the period up to 2030 and identify key tasks for implementation during the twelfth Five-Year Plan.

Although China is moving forward on CCS RD&D, there is to date limited progress in developing legal and regulatory frameworks for the introduction of CCS. Such regulations will be needed to support the demonstration and deployment of CCS in China, particularly for the storage of CO_2 underground but also to address the safety of pipelines carrying supercritical CO_2, and the environmental impact of CCS plants. There are also issues such as long-term liability and financial responsibility post-closure that need to be addressed. To an extent, this reflects the NDRC concerns that CCS is at present too expensive to deploy in China without significant international subsidy and that even then there would be resource implications with the need for increased coal supplies to offset the energy efficiency penalty as well as water availability issues to be addressed.

3.5 International accords on climate change

China has ratified the primary international accords on climate change, ie the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. Since it is classified as a developing country, China has no emission limits under either accord. However, it has been a major recipient of Clean Development Credits for a wide range of energy-related projects across many sectors, having sold some 229 Mt of certified emission reduction credits under the UN-backed Clean Development Mechanism (CDM) since 2005, which is about half of the total, worldwide (Bloomberg News, 2010).

An important international policy decision that could help China to implement CCS, alongside the energy efficiency initiatives and the introduction of renewable energy sources, was taken at the UNFCCC in Mexico in December 2010. It was agreed to include CCS projects under the CDM with rules regarding CCS projects to be finalised at the next climate talks in December 2011, including issues such as permanence, boundaries and safety to be addressed and resolved. In effect, this agreement recognised that CCS has a critical role to play as part of a portfolio of actions in reducing global CO_2 emissions and the UN decision will provide a support mechanism that may well clear the way for developing countries to finance CCS projects (Carbon Capture Journal, 2010b, 2011a).

4 Overview of Chinese CO_2 emissions

In recent years, there has been considerable concern expressed regarding the very rapid annual growth in CO_2 emissions from China, although when expressed either on a historical cumulative basis or on a per capita basis, they are considerably lower than, say, those of the USA and Europe. Nevertheless, China is a major CO_2 emitter at a level that represents a significant portion of current global GHG emissions, due to the rapid industrialisation of the country and the use of coal as the major fuel in power generation and other industrial sectors.

4.1 CO_2 emissions by source

In 2008, China emitted 6.5 Gt CO_2 from fossil fuel combustion, about 85% of its total, of which about 5.5 Gt were released from coal (IEA, 2010b). For 2010, the total CO_2 emissions were 8.3 Gt (Reuters, 2011), with coal thought to account for over 6 Gt. Although the majority of coal use was for power generation, there was significant use in a number of industrial processes, as indicated in Table 2, which provides a broad correlation to CO_2 emissions from each of the respective sectors.

Table 2 Breakdown of coal use within the Chinese industrial sectors for 2010 (Mao, 2011)

Sector	Coal use, Mt	Proportion of coal use, %
Power generation	1765	54.8
Iron & steel	515	16.0
Building materials	515	16.0
Chemicals	171	5.3
Others	245	7.6
Export	10	0.3

Although in absolute terms, CO_2 emissions have risen strongly in recent years, carbon intensities have reduced in these sectors (Climate Policy Initiative, 2010). During the period of the eleventh Five-Year Plan, the carbon emission intensity in coal-generated electricity decreased by 7.7%, through the closure of some 80 GWe of small power plants and the extensive introduction of large coal fired units with state-of-the-art efficiency and environmental performance (Minchener, 2010; UNDP, 2010). When the introduction of non-fossil fuel power plants is also considered, the total decrease in carbon emissions per unit of power generation was 8.1% over the period 2006-09 (UNDP, 2010).

With regard to the manufacturing sector, much of this comprises high emission industries, such as steel and cement. From 2005 to 2008, energy consumption per unit of added value decreased by 23.5% and carbon emissions per unit of added value decreased by 25.1%. This was achieved through technology improvements in the largest enterprises, by phasing out old technologies and introducing energy-efficient equipment, together with structural changes by shifting to less energy-intensive industries (UNDP, 2010). Although a much smaller sector in terms of total coal use compared to steel and cement, the chemicals sector is moving in a similar direction, with the introduction of high efficiency modern gasifiers, as discussed in Chapter 8.

4.2 Current and projected future CO_2 emissions

The EIA, in its energy projections to 2035 suggests that if China does not make any changes to its energy mix and utilisation approach then it would most likely account for about 23% of global energy consumption by 2030 (EIA, 2010a). On such a basis, China's coal-related CO_2 emissions would grow by an average of 2.6%/y, from 5.5 Gt in 2007 to 10.6 Gt in 2035 (EIA, 2010b). The expectation is

<table>
<tr><th colspan="6">Table 3 Projection for China's total installed electric power generation capacity from 2015-50 (Mao, 2011)</th></tr>
<tr><th colspan="2"></th><th>2010</th><th>2015</th><th>2020</th><th>2050</th></tr>
<tr><td colspan="2">Total installed net power plant capacity, GWe</td><td>963</td><td>1437</td><td>1730</td><td>2900</td></tr>
<tr><td colspan="2">Coal, GWe (%)</td><td>687 (71.4)</td><td>933 (65.3)</td><td>960 (55.5)</td><td>1400 (48.3)</td></tr>
<tr><td colspan="2">Natural gas, GWe (%)</td><td>20 (2.0)</td><td>40 (2.7)</td><td>60 (3.5)</td><td>100 (3.5)</td></tr>
<tr><td colspan="2">Hydro, GWe (%)</td><td>213 (22.1)</td><td>324 (22.0)</td><td>350 (20.3)</td><td>400 (13.8)</td></tr>
<tr><td colspan="2">Nuclear, GWe (%)</td><td>11 (1.1)</td><td>43 (2.9)</td><td>70 (4.0)</td><td>300 (10.3)</td></tr>
<tr><td rowspan="3">Renewables</td><td>Wind, GWe (%)</td><td>30 (3.1)</td><td>70 (4.8)</td><td>250 (14.4)</td><td>400 (13.8)</td></tr>
<tr><td>Biomass, GWe (%)</td><td rowspan="2">2 (0.2)</td><td rowspan="2">27 (1.8)</td><td>20 (1.1)</td><td>100 (3.5)</td></tr>
<tr><td>Solar, GWe (%)</td><td>20 (1.1)</td><td>200 (6.8)</td></tr>
</table>

Note:
1. The projection of China's total installed power capacity is based on information collected from representatives of the China Electricity Council (CEC), the NDRC and Tsinghua University
2. The data for 2010 were issued officially by the CEC, early in 2011
3. The data for 2015 represent the official goal of the twelvth Five-Year Plan (2011-15)
4. The projections of China's total installed power capacity for both the medium term (2020) and the long term (2050) are at best indicative with many assumed conditions. As such they should not be in any way considered as official projections by the Chinese Government

that, over the period to 2035, the power sector dominance would increase markedly. For non-power coal use, while coal use is expected to increase, the relative importance of each subsector may well change.

However, projections for energy use and CO_2 emissions could change significantly as China's new policies and regulations, aimed at reducing greenhouse gas emissions, are introduced (EIA, 2010b). As was described previously, the State Government has determined to cut both energy intensity and carbon intensity per unit of GDP through to 2020 compared to 2005 levels, the implementation of which will comprise a massive energy efficiency programme together with promotion of the use of natural gas, nuclear power and renewables. Even so, there will still be a continuing extensive introduction of larger high-efficiency coal power plants and it is assumed that coal use will increase although it has been stated that China will limit annual coal utilisation to between 3.6 and 3.8 Gt for the period 2011-15. If achieved, this would represent a 3.5%/y growth for 2011 to 2015, which is considerably lower than the average 8.1%/y growth for 2007 to 2010 (Sxcoal, 2010b).

Table 3 provides a preliminary estimate of the power sector energy mix for the period to 2050. This provides firm data on the situation at the end of 2010, the official plan for the twelfth Five-Year Plan together with some indicative estimates of likely coal power capacity for 2020 and 2050. Consequently, annual CO_2 emissions will still increase compared to 2005 levels (Wall Street Journal, 2011). However, there is a broad agreement from a number of modelling studies that eventually, after 2020, as the energy efficiency initiatives show a significant impact and the introduction of low and zero carbon fuels in place of coal becomes reasonably significant, Chinese annual CO_2 emissions will at least reach a plateau. Some examples are outlined below.

The China Energy and CO_2 Emissions Report is a major study that has been undertaken by the NDRC and the Development Research Centre of the State Council. This suggests that the increase in China's CO_2 emissions could slow after 2020 and broadly peak at around 2030, subject to the Government continuing with rigorous policies to improve energy efficiency and provided that it accelerates exploitation of renewable energy (China Daily, 2009). Under such a scenario, current annual CO_2

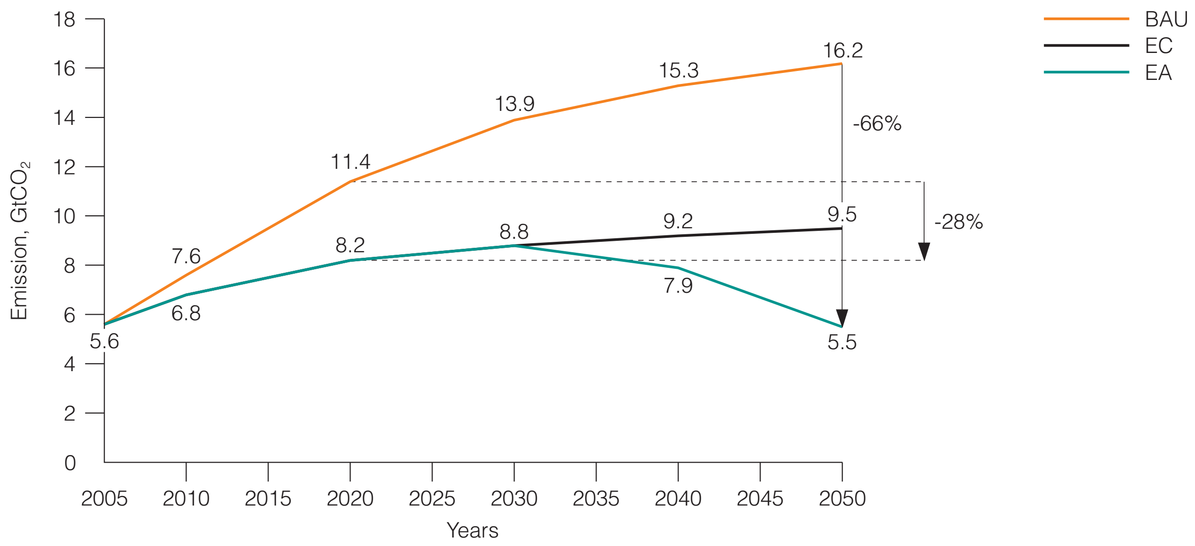

Figure 5 Future emissions scenarios (UNDP, 2010)

emissions from fossil fuel use, which were 6.5 Gt in 2007, may reach 9 Gt by 2030, after which the level will decline to some extent (Sxcoal, 2010a; Reuters, 2009a).

The study was significant in that it proposed the setting of relative and then absolute targets for limiting China's emissions of man-made greenhouse gases. These could include carbon intensity goals (as have been introduced) followed at some point by absolute caps on emissions, also allowing for the emergence of a 'cap-and-trade' market so companies could buy and sell emissions rights, domestically and internationally (Reuters, 2009b). This would also entail China continuing and increasing its massive investment in low-carbon technology R&D, with the expectation that such a huge investment could keep China's economy growing at a fast pace and make China a global leader for the supply of nuclear, wind and hydropower technologies and electricity transmission.

The United Nations Development Programme (UNDP) produced a human development report for China, which included the modelling of three energy scenarios through to 2050, the projected CO_2 emissions for which are shown in Figure 5 (UNDP, 2010).

In a Business as Usual (BAU) scenario, Chinese policymakers recognise the prime importance of economic growth and development, but impose certain extra policies that include eliminating outdated production capacity to adjust the economic structure. Under such a scenario, energy demand would increase by 2.6%/y between 2005 and 2050, to reach 7.1 Gt of coal equivalent by 2050, which would be an overall increase of 220%. The average growth in demand between 2010 and 2020 would be 4.3%, before slowing down and tapering off to an average 1%/y from 2030 to 2050. Under this scenario, coal would remain the dominant source of primary energy, but with a smaller share. Oil would still be the second largest source with a slightly raised share, while demand for natural gas, nuclear power, and non-hydro renewable energy technologies would increase sharply although their respective shares would still be relatively small. The share of hydropower would remain almost constant. Consequently, China's energy-related CO_2 emissions would increase rapidly to 11.4 Gt in 2020, 13.9 Gt in 2030 and 16.2 Gt in 2050. There would not be a peak before 2050.

The Emissions Control (EC) scenario considers the maximum potential for reducing CO_2 emissions without causing an economic recession. In this scenario, China implements a package of industrial and energy structure policies to reduce growth related energy consumption, as its contribution to the global response to climate change mitigation. This includes adopting advanced measures for improvements in energy efficiency and the development of renewable energy, but not applying CCS, nor solar power generation and electric automobiles on a large scale. Under this scenario, China's demand for primary energy would also increase until 2050, but at a slower rate compared to the 'Business as Usual' scenario, due to the large-scale use of low carbon energy sources. Demand would increase by 2.1%/y and reach 5.7 Gt of coal equivalent by 2050. The proportion of coal in the primary energy mix would drop sharply to 44% while the share of non-hydro renewable energy and non-fossil fuel energy sources would increase. Compared to the reference scenario, CO_2 emissions under this control scenario would be lower by 3.2 Gt in 2020, 5.1 Gt in 2030 and 6.7 Gt in 2050. CO_2 emissions intensity per unit of GDP would decrease by 51% in 2020, 69% in 2030 and 85% in 2050 compared to the 2005 level. Considering the need for sustainable and stable social and economic development, it is considered unlikely under this scenario that China's emissions would peak before 2050.

Under the Emissions Abatement (EA) Scenario, policymakers would set 2030 as the year China reaches peak emissions, while realising the maximum possible reduction in emissions by 2050. In addition to the previous measures, this would require the widespread introduction of more expensive low carbon technologies such as electric motors, fourth generation nuclear power as well as CCS, together with incentives to encourage further new renewable technologies, particularly wind and solar power. Under such a scenario, energy demand would increase by 2%/y and reach 5.5 Gt by 2050, much less than under the BAU scenario. With the large-scale use of low carbon energy sources, the proportion of coal in the primary energy mix would drop sharply to 36%, while the share of non-hydro renewable energy and non-fossil fuel energy sources would increase. With regard to CO_2 emissions, it is suggested that it would be technologically possible for China's emissions to peak in 2030. At the same time, it was noted that this would be difficult without the effective implementation of a large number of support measures over the next few years, as China would otherwise have to bear large social and economic costs. Under this scenario, for 2050, CO_2 emissions would decline to below 5.5 Gt while emissions intensity would decrease by 91% compared to 2005 levels.

Finally a recently released study by the Lawrence Berkley National Laboratory (LNBL) also suggests that CO_2 emissions could be constrained but in this case it is assumed that, rather than significant use of CCS, there will be a massive increase to over 550 GWe of nuclear power (Lawrence Berkeley National Laboratory, 2011).

4.3 Implications arising

It is stressed that these studies represent possible scenarios, and in all cases the inputs and assumptions are a matter of debate. For example, under the more environmentally driven options of the NDRC and UNDP studies, both of which were undertaken primarily by Chinese researchers, even though CCS introduction is envisaged, the Chinese Government would have to close a significant proportion of its new, modern, clean coal power stations, all of which could normally be assumed to be available for operation until 2050. This seems unlikely. In the case of the LNBL study, the required massive increase in the use of nuclear power also seems unlikely, not least given international concerns over this technology following the problems in Japan. Nevertheless, all such studies indicate the major issues that need to be addressed if China's CO_2 emissions are to at least peak in absolute terms. Given China's focus on energy security, the continued use of coal for power generation would appear inevitable and as such CCS must be a promising option for carbon mitigation.

5 China's national CCS R&D programme

The national R&D programme is framed within the principles of China's Scientific and Technological Actions on Climate Change, the aims of which are to combine government leadership with enterprise participation, to link technological research with policy studies, to ensure short-term demands can be compatible with long-term objectives, and to co-ordinate overall planning with separate implementation (MOST, 2007a). Targets to be met by 2020 include:

- significant improvement in the capacity for independent innovations in research on climate change;
- making breakthroughs in the wider applications of social and economic areas of key technologies related to GHG emissions control and climate change mitigation;
- enhancing the adaptive capability of key sectors and typically vulnerable areas in response to climate change;
- improving the ability of science and technology (S&T) to support international cooperation, engagement and decision making on climate change;
- improving S&T infrastructure, research conditions and qualifications of research teams;
- enhancing public awareness of climate change and related scientific knowledge.

In terms of technological development for GHG emission controls and climate change mitigation, there is some focus on CO_2 capture, utilisation and storage technologies, through the development of key technologies, the design of a technology roadmap for CO_2 capture, utilisation and storage; and by engineering and implementing a technical demonstration project (NZEC, 2009a). It should be noted that China has stressed that it will pay special attention to the research and development of new and innovative methods and technologies to use captured CO_2 as a resource (MOST 2010).

5.1 National key technologies R&D programme for CCS

This programme, which is funded by MOST, includes strategic studies focused on the applicability of CCS in China, and the associated impact on energy systems and GHG emission reduction (MOST, 2007b). The participants include organisations such as ACCA 21 and the Energy Research Institute of the NDRC. Aspects of their work were considered in Chapter 4.

Since the latter stages of the tenth Five-Year Plan (2001-05) and then during the eleventh Five-Year Plan, the major practical research activities were undertaken within the 973 and 863 R&D programmes. Thus:

- the National Basic Research (973) Programme includes a major programme of fundamental research on CO_2 use for EOR applications and long-term storage, on syngas production from coal gasification and pyrolysis, and the high efficiency conversion of natural gas and syngas either for chemical products or for carbon free use in gas turbines; while
- the National High-Tech Research and Development (863) Programme includes several projects to develop advanced CO_2 capture technologies based on adsorption and absorption processes, and to explore CO_2 storage technology.

For all of this R&D work, the aim is to establish Chinese based techniques upon which can be secured independent intellectual property rights. An outline of each key project is given below.

973 Project 1: Utilising greenhouse gas as resources in enhanced oil recovery (EOR) and geological storage

The various participants include PetroChina, Institute of Geology and Geophysics (Chinese Academy of Sciences), Peking University, China University of Petroleum, Huazhong University of Science and Technology, Tsinghua University, and the operators of the Jilin oilfield.

This project has examined four key scientific issues:
- geological issues associated with CO_2 storage;
- physical and chemical issues during CO_2 injection and storage;
- non-linear flow mechanics during the CO_2 injection process;
- CO_2 capture and corrosion prevention.

The work comprised:
- evaluation of the potential for CO_2 storage to fit China's geological characteristics;
- development of a theoretical understanding of the geological issues for CO_2 subsurface storage;
- development of a theoretical understanding for monitoring and predicting CO_2 storage processes;
- research on multiphase and multi-component phase theory during CO_2 injection for EOR;
- research on non-linear flow mechanisms and principles of multiphase and multi-component flow during the CO_2 injection process;
- establishment of the principles of O_2/CO_2 circulating combustion for coal and the mechanism of synergetic removal of pollutants;
- development of a theoretical understanding of the technology of CO_2 separation and concentration from coal combustion;
- understanding the theory and method of preventing CO_2 induced corrosion.

The expected outputs of the project are to:
- establish a long-term CO_2 geological storage technology system applicable to China's situation;
- bring about the social benefits from CO_2 emissions mitigation and the economic benefits of efficient CO_2 utilisation;
- develop and advance theories for multiphase and multi-component phase flow during CO_2 separation and concentration;
- ensure capacity building for the development and implementation of CO_2 emission reduction and efficient utilisation;
- establish China in a leading position globally, with independent intellectual property rights for CO_2 emission mitigation combined with efficient utilisation.

973 Project 2: Fundamental research on syngas production through coal gasification and pyrolysis

This project has been undertaken by Taiyuan University of Technology, Tsinghua University, China University of Petroleum (Beijing), Institute of Coal Chemistry of the Chinese Academy of Sciences (CAS), East China University of Science and Technology, Xi'an Jiaotong University, Institute of Engineering Thermophysics (CAS) and the Research Institute of Petroleum Exploration & Development.

The focus of the research has been into syngas production as a means to support development of a multi-generation system based on partial coal gasification and pyrolysis that will help realise low-cost, high efficiency and lower pollution power generation. The work has focused on:
- fundamental understanding of large-scale gasification and syngas production based on coal;
- fundamental understanding of catalyst synthesis for the fuel slurry reactor;
- engineering of the reactor;
- combustion of both hydrogen rich and unshifted syngas;
- research on the special conditions of dual gas multi-generation systems and design together with the development of an optimisation theory for complex systems.

973 Project 3: Fundamental research on the high efficiency transfer of natural gas and syngas

The objective of the project is to study the high-efficiency conversion of natural gas and syngas into high quality liquid fuels and high added-value chemicals for lower cost transportation. This has been undertaken by Dalian Institute of Chemical Physics (CAS), Institute of Coal Chemistry (CAS), Nanjing University, and Xiamen University.

This project aimed to undertake dynamic research on catalyst theory and concepts, including research into optimum catalyst reaction conditions, starting with the development of a new catalytic reaction and new catalytic materials followed by an in-depth study of the optimum micro-structure and macro-structure for natural gas and syngas. It comprised eight research topics, which covered:

- investigation of key problems of syngas production from natural gas, relating to large-scale hydrogen production and CO_2 handling;
- ensuring high quality liquid fuels from syngas;
- development of production processes for oxygen containing compounds from syngas;
- development of high temperature fuel cells based on syngas and natural gas;
- optimisation of existing techniques for the direct conversion of methane into methanol;
- investigation of novel processes for the direct conversion of methane into methanol;
- examination of the relationship between structure and activity and dynamic properties of catalysts and catalyst systems;
- investigation of micro-mechanisms and the identification of intermediates during the catalytic process.

973 Project 4: A study of high efficiency heat transfer in gas turbines

This project is concerned with the fuel chemical release, heat-work transfer process, integration of heat & work, hydrogen production by gasification, technology fundamentals, system characteristics & optimisation of an advanced humid-air gas turbine cycle. There is participation by the South China University of Technology, Huazhong University of Science and Technology, Tianjin University, Sichuan University, Zhejiang University, Lanzhou Institute of Chemical Physics (CAS), University of Science and Technology of China, China University of Mining & technology, East China University of Science and Technology, Southeast University, Guangzhou Institute of Energy Conversion.

The aim is to define the energy system's process structure and composition and to develop and establish the technological fundamentals of system characteristics and optimisation of the advanced humid-air gas turbine cycle. The work comprised:

- research on the macromolecular structure of biomass and response mechanisms under thermo-chemical circumstances;
- fundamental research on the biomass gasification;
- fundamental research on biomass selective pyrolysis;
- research on the selective control law of the complex bio-oil catalytic process;
- research on the characteristic molecular properties and separation of bio-oils;
- examination of reaction mechanisms and fundamental laws of hydrogen production by reformation of bio-oil;
- research on the mechanisms involved in the catalytic synthesis of liquid fuel by CO_2-rich biomass.

863 Project 1: Development of carbon capture and storage

This project aims to develop advanced international CO_2 capture technologies such as adsorption and absorption and to explore CO_2 storage technology. The partners include those involved in the complementary 973 project. The three research topics include:

- examination of the applicability of high efficiency CO_2 absorption solvents, including the fillers for the absorber, development of new high efficiency absorption/separation equipment and technologies, together with modelling and optimisation of process integration;
- assessment of high efficiency CO_2 adsorption materials, modelling of CO_2 adsorption together with the development of new techniques plus optimisation of process integration;
- assessment of off-shore and saline aquifer CO_2 storage technologies. This will include examination of techniques for establishing storage capacity and the monitoring of gas storage integrity.

863 Project 2: Integrated research on CO_2 emission reduction, and its resource recycling, low NOx combustion, SOx control and multi-pollutants removal

The project is an application study on integrated control of multiple pollutants in coal-fired power

plants, which has been undertaken by the National Power Station Combustion Engineering Research Centre and Shenyang Normal University. The project comprises three parts:
- research on coal combustion, control and analysis of CO_2 emissions reduction and multiple pollutants;
- development of an integrated system for eliminating CO_2 and multiple pollutants from flue gas;
- testing and characterisation of the integrated system on a large-scale rig.

Oxyfuel combustion R&D
MOST is also supporting longer-term technology development programmes. For example, the Huazhong University of Science and Technology in Wuhan has carried out extensive fundamental research on oxygen-fired coal combustion, leading to the establishment of a 400 kWth test unit. This can operate in a staged combustion mode either with air or O_2/CO_2 together with the use of a calcium-based sorbent within the furnace for desulphurisation. The construction of a 3 MWth pilot plant is essentially complete with commissioning scheduled by the end of 2011 (MOST, 2011b). There are also provisional plans to build a 35 MWth industrial pilot unit in Yingcheng, Hubei Province, with up to 100,000 t/y of captured CO_2 being stored in nearby deep salt mines. This project is at the engineering design stage (MOST, 2011b).

The Southeast University in Nanjing is undertaking a similar programme, having undertaken extensive laboratory trials using coal and coal/biomass feedstocks, with emphasis on assessing the performance of various coal types including impacts on pollutant emissions. It is now planning with Babcock and Wilcox (USA) to establish a 2.5 MWth test unit at the University (Zhou, 2011) for which the design is completed with engineering and construction scheduled to be finished by the end 2012.

Chemical looping combustion R&D
There is a range of activities being undertaken at various universities covering longer-term capture possibilities such as chemical looping, the driver being to reduce the costs and energy penalty (Dong, 2011). This includes work at the North China Electric Power University and the South East University. The latter has undertaken considerable small-scale rig trials, with firing primarily on gas but also some trials on coal, with low-cost iron-based oxygen carriers, as well as cold modelling and CFD simulations. This has led to construction of a 100 kW interconnected fluidised bed-based coal-fuelled unit, which will begin operation in the near future (Rui, 2011). The aim will be to improve the reactivity of the iron-based carriers, assess alternative carriers, and to determine the effect of scale-up on unit operations.

Preliminary assessment of CO_2 potential storage capacity in China
Work on this very important topic has formed a key part of various international collaborative activities since 2006 (*see* Chapter 9). Alongside these ongoing activities, in 2009 the China Geological Survey initiated the 'Potential Capacity and Evaluation at CO_2 Geological Storage in China Project' while the Ministry of Land and Resources included the investigation and evaluation of CO_2 geological storage capabilities in the monitoring and evaluation of global climate change (MOST, 2010). Investigations of underground storage resources were also included in the Geological Mineral Support Engineering Programme (2010-20). Some universities and research institutions, including Tsinghua University, the Institute of Rock and Soil Mechanics of the Chinese Academy of Sciences and the Institute of Geology and Geophysics at CAS have begun research on the physical characteristics of CO_2 storage sources and sinks in various provinces. The preliminary results suggest that some 98% of the potential storage capacity will be based on saline aquifers (MOST, 2011b).

5.2 Other university research on CCS

Alongside the MOST activities, various universities receive funding from the National Science Foundation, which supports fundamental research, including aspects of CCS (Wang, 2011b). Such support can be either separate from or complementary to MOST. For example, the Department of

Thermal Engineering at Tsinghua University and the Institute of Thermal Power Engineering at Zhejiang University are both engaged in extensive research into chemical absorption for post-combustion capture, comprising additives to enhance amine scrubbing, ammonia scrubbing, as well as use of membranes for O_2 and CO_2 separation (Wang, 2011a; Fang, 2011). Tsinghua University is also concerned with the investigation and analysis of CO_2 sequestration such as Enhanced Coal Bed Methane (ECBM) techniques (Wang, 2011b). The department is also engaged in CCS policy studies including inclusion of CCS in the CDM. At Shanxi University, the Institute of Low Carbon Development was established in April 2010, to undertake low carbon theoretical research applicable to the situation within Shanxi Province (Gassnova, 2010).

As well as direct CCS research, there is also an ongoing materials development and testing programme to provide options for increasing the steam temperature and, hence, cycle efficiency of ultra-supercritical coal-fired power plants. This offers the prospect of countering the CO_2 capture efficiency loss through higher efficiencies of the associated power plant (Mao, 2011).

Alongside these projects, which focus on the power sector, there are also some very preliminary studies about CO_2 capture options for iron and steel, cement and other industry sectors (Wang, 2011b; Qian, 2011).

6 CO_2 utilisation activities by Chinese industry

It is important to note that China is very much focused on the utilisation of CO_2, as a means to enhance energy security, with emphasis on developing the use of CO_2 for EOR applications. To put this interest in EOR in context, China has proven overall oil in place (OOIP) in low-permeability reservoirs of 6.32 Gt. This represents 28.1% of the total proven OOIP and is mostly located in the northern and eastern parts of the country. These fields are not particularly suitable for the use of traditional water flooding EOR techniques and CO_2 EOR may be a more promising option to improve the oil recovery. Consequently, a series of large-scale trials by major oil companies is underway, which are a direct scale-up and development of the research undertaken within the 973 Programme (Zhang, 2010).

There is also work under way by various companies to create added value by converting CO_2 into industrial products (MOST, 2010).

6.1 PetroChina CO_2 EOR project

PetroChina has carried out CO_2 EOR-related activities since 1990, which initially included some very small ad hoc injection trials in various oil wells. In 2005, PetroChina discovered some large natural gas deposits at Changchun that contained high levels (up to 22.5%) of CO_2, which had to be removed prior to the natural gas being utilised. Rather than emit the CO_2 to atmosphere, it is now being stripped and condensed before being injected at industrial pilot scale into oil wells to enhance oil recovery as well as to establish some level of geological storage (Zhong, 2010). Thus since 2006, PetroChina has been undertaking China's first major project for CO_2 EOR at the Jilin Oilfield, Liaoning Province, with a total investment of 2 billion RMB that is funded in part by the MOST 973 Programme (Carbon Capture Journal, 2011b). Annual injection rates were initially some 10,000 t but since 2009 these have been increased at some of the injection sites, which are designated as longer-term projects in order to continue to gain relevant technical experience (Bo, 2010).

By the end of May 2010, some 120 ktCO_2 had been injected with about 80 kt being retained in the oilfield and an additional 50 kt of oil being extracted (Bo, 2010). It is intended to increase the injection rate since the current annual availability of CO_2 is 200–300 kt from a total estimated recoverable reserve of 12.5 billion m^3 CO_2. The longer-term aim for 2015 is to achieve an annual additional oil extraction of 500 kt, with a CO_2 storage capacity of some 0.8–1.0 Mt (MOST, 2010).

PetroChina reports that, in some cases, oil recovery through CO_2 injection may be enhanced by 10–20%. Additional trials are to be undertaken by Petrochina in the Daqing and Changqing Oilfields (Bo, 2011).

6.2 Sinopec CO_2 EOR project

Sinopec has undertaken some EOR activities in the Shengli oilfield of Shandong Province (Zhang and others, 2011). Starting in 2007, Sinopec established an industrial pilot scale trial of CO_2 enhanced EOR and in late 2010 it began operation of a post-combustion capture system with MEA as the solvent at the Shengli power plant to provide CO_2 with a purity of 99.5%. It then used the concentrated gas to flood a block within the Zhenglizhuang oil well, with subsequent separation and reinjection of the gas to enhance the rate of CO_2 underground storage. Sixteen production wells had been drilled in this block before the CO_2 flooding pilot test was carried out, most of which were fracturing production wells that were water free with initial high production rates. The overall injection rate was some 80–100 t/d and, as of April 2011, the amount of CO_2 injected was some 11 kt, which is believed to have resulted in a cumulative oil increment of some 6 kt (Zhang, 2010). On the basis of these provisional results, it is suggested that the overall oil recovery rate could be increased by 5% to 15%. Sinopec established a CO_2 real-time detection device in order to measure the flux of injected CO_2. Their results suggest that about 60–70% of the CO_2 is permanently sealed in the ground while the remainder is removed with the extracted oil. There are provisional plans for MOST to support a 1 Mt/y CO_2 EOR demonstration project in the oilfield for operation by 2014 (MOST, 2011).

6.3 ENN resource recycling of CO_2

The ENN Group project portfolio focuses on gas distribution and the exploitation of coal-based clean energy, including zero emission hydrogen energy and bio-energy by recycling treatment for CO_2. In Dalate, Inner Mongolia, ENN are attempting to use algae to absorb CO_2 for subsequent processing to produce biodiesel. The aim is to establish a clean energy industry chain by cultivating microbes with high oil content, which can quickly and efficiently absorb CO_2 due to their rapid photosynthesis. The intention is to establish a facility with an annual CO_2 input capacity of 320 kt (Zhang, 2010). The concentrated CO_2 source will be provided from the waste gas of a nearby coal to methanol and dimethylether plant.

Results to date have not been published although it is understood that breakthroughs have been made in some core technologies with the basis for a demonstration project outlined.

6.4 Jinlong-CAS CO_2 utilisation for chemicals production pilot project

In Taixing, Jiangsu Province, the Jinlong-CAS Chemical Co Ltd has built a production line to produce 22 kt/y of CO_2-based polypropylene(ethylene) carbonate poly-oil, which can subsequently be used to manufacture a highly flame-retardant exterior wall insulation material. The CO_2 source will be provided as gas captured from ethanol production plants. There are various plans to expand the production line in the period to 2016 (MOST, 2010).

7 CCS in the coal power generation sector

China is the world leader for introducing advanced PC based units, with 600 MWe supercritical (SC) and 660–1000 MWe ultra-supercritical (USC) units being established in great numbers (Minchener, 2010). At the end of 2010, the number of PC units with SC and USC steam conditions either in operation or at the design/construction stage was close to 450 GWe (Mao, 2011). Alongside this, there are various developments to establish a 600 MWe CFBC power plant with SC steam conditions. All units are being manufactured in China at costs significantly below OECD levels, with, for example, a specific capital investment of 3495 RMB/kW (550 US$/kW) being quoted for a 1000 MWe PC USC unit not including the FGD (Minchener, 2010).

With regard to CCS, there are several industrial-scale CO_2 capture and utilisation activities that are being taken forward by the major Chinese power generation companies (Belfer Centre, 2010). These include the large-scale trials for PC-based post-combustion CO_2 capture systems being undertaken by the Huaneng Power Group and the range of activities being established by the China Power Investment Corporation. In addition, the GreenGen consortium is about to demonstrate its own IGCC technology to which pre-combustion CO_2 capture is likely to be added in due course, subject to successful operation of the gasification-based power generation system. With regard to CO_2 utilisation, the focus is on using the CO_2 for a range of industrial applications, including in the food and beverage industries.

7.1 Huaneng Power CO_2 capture and utilisation projects

Figure 6 Main structure showing the CO_2 stripper (left) and absorber (right) on the sidestream from the Gaobeidian PC CHP plant in Beijing

For CO_2 capture on coal-fired power plants, Huaneng Power has led the way. Following co-operation with Australia's Commonwealth Scientific Industrial Research Organisation (CSIRO), a post-combustion CO_2 scrubber test facility was designed by the North China Power Engineering Co Ltd. and supplied by the Thermal Power Research Institute (TPRI) for installation on the 800 MWe Gaobeidian PC CHP plant in Beijing (*see* Figure 6). Almost all the equipment was manufactured in China apart from a limited number of valves, which had to be imported.

The test unit is located on a sidestream after the deNOx SCR, ESP and FGD units, and takes 1% of the exhaust gases (Liu, 2008). The design parameters are:
- flue gas flow to unit 2000–3000 m^3/h;
- steam consumption 3 GJ/tCO_2;
- solvent consumption <1.35 kg/tCO_2;
- annual CO_2 capture capacity 3000 t.

Operations began in mid-2008, with the aim to gain experience of the technology and to undertake parametric studies relevant to Huaneng's assessment of post-combustion capture for possible future application. This has included the impact on performance of operational changes, to evaluate alternative capture solvents (the baseline is the CSIRO lean MEA) and to learn about component materials issues.

Figure 7 CO_2 refining unit, showing transfer of 'pure' CO_2 to transport vehicle at the Gaobeidian PC CHP plant in Beijing

Figure 8 The CO_2 stripper, absorber and spherical storage tanks on the sidestream from one of the 660 MWe ultra-supercritical units of the Shidongkou No 2 PC Power Plant in Shanghai (Liu, 2011)

The captured CO_2 has a purity of 99.9%. This is refined to give a 99.997% pure product that is sold to a local soft drinks company. The CO_2 is stored in a vessel on site and collected by tanker every 3–4 days (*see* Figure 7).

Huaneng Power, with some financial support from MOST, has now taken this much further with a post-combustion CO_2 capture facility on the Shidongkou No 2 Power Plant in Shanghai (Chinacsr, 2009). This plant comprises 2 x 660 MWe coal-fired USC units to which has been added a sidestream that processes 3% of the flue gases with an annual CO_2 capture capacity of 120,000 tonnes (*see* Figure 8). At the same time, Huaneng reached an agreement with the Shanghai Electric Corporation to establish a joint Greenhouse Gas Mitigation R&D Centre, which includes CCS activities. This arrangement has been formally endorsed by the Shanghai Municipal Government.

The system commenced operation early in 2010 and has operated efficiently on a near-continuous basis, while allowing staff from the Clean Energy Research Institute of Huaneng Power to undertake various assessments and parametric studies (Power, 2010). The purity of the captured CO_2 is about 99.9%, which is processed further to give a value of 99.997%. All of the captured CO_2 is sold to industrial enterprises in and around Shanghai, where the annual market for CO_2 is about 150–180 kt. There are two CO_2 holding tanks on site with a total capacity of some 1200 tonnes, which is approximately the amount captured in 100 hours operation (Liu, 2011). These tanks are regularly emptied and the CO_2 transferred to the customers. However, if for any reason there is a slump in demand, which in the food and beverage industries is to an extent seasonal, then the capture facility is not operated once the tanks are full. Currently, the system has been disconnected for some equipment upgrade and improvements to the efficiency of the steam system for the capture/stripper units. It is expected to recommence operation at the end of 2011.

It is understood that total investment was lower than the planned RMB150 million (US$23 million), although the basis for this reduction has not been explained. Huaneng are claiming that the cost for capturing the CO_2 is below 200 RMB/t (30 US$/t), rising to 35 US$/t when the gas has to be purified for use in the food and beverage industry (Liu, 2011). This is some 30% of the costs quoted for OECD intended projects. It is not clear whether this difference is merely a reflection of China's lower equipment cost base or whether Huaneng has made some significant process improvements (Nature 2011; Carbon Capture Journal, 2011b). Certainly, it is understood that Huaneng has made some unspecified changes in the design of the plant compared to the smaller Gaobeidian plant while the solvent used in the scrubber system is a mixture of ethanolamine and additives with some modifications to the overall chemistry. This is believed to have been developed by the Research Institute of the Sinopec Nanjing Chemical Company (MOST, 2010).

The intended lifetime of the project is not fixed and, as the CO_2 capture costs are covered by the sales of the CO_2 operations, the sidestream could continue for some while. There is also the intention to offer the use of this industrial pilot plant to possible overseas partners that have alternative CO_2 capture solvents that they would like to test under realistic coal-fired power plant conditions (Liu, 2011).

Huaneng Power has undertaken a feasibility study to scale up capture operations to 1 Mt/y with the CO_2 being used for EOR. They are in discussion with the NDRC and NEA about how this might proceed, which includes consideration of some form of international co-operation as one possible option. Currently, they are very wary of undertaking such a major scale-up on their own given the uncertainty of CO_2 EOR as a revenue stream and the continuing poor returns being achieved by the power generating companies due to their rising coal costs and fixed electricity sales prices (Minchener, 2010).

7.2 China Power Investment Corporation CO_2 capture project

In 2010, a sidestream CO_2 capture facility was established at the Hechuan Shuanghuai Power Plant in Chongqing, which is owned by the China Power Investment Corporation (CPIC). The plant comprises two 300 MWe subcritical units and some 50 million m^3 of flue gas can be processed annually, which is equivalent to less than 1% of the coal fired power plant's throughput (Gasworld, 2010). This gives an annual industrial grade CO_2 capture capacity of 10 kt. The test facility was designed and built with domestic equipment by the Yuanda Environmental Protection Engineering Company Ltd, a subsidiary of CPIC (*see* Figure 9). It forms part of a comprehensive gas cleaning test centre, with other facilities for testing desulphurisation systems and the removal of NOx and mercury. Total capital investment is understood to be some RMB12 million (~US$2 million). The solvent is MEA. Currently, the unit is being tested over a range of conditions and is not in continuous operation. The purity of the captured CO_2 is about 99.5% (Yang, 2011). As with the Huaneng capture facilities, the CO_2 is sold to local enterprises, in this case mostly for use in welding activities (MOST, 2011b). It is understood that the cost for each tonne of CO_2 captured is RMB394 and since the selling price in the region is about RMB620, it should be possible, under continuous operation, to achieve an annual profit of over RMB2.26 million, which would represent a payback period of 5–6 years.

Figure 9 CO_2 capture facility at the CPIC Hechuan Shuanghuai Power Plant in Chongqing

There are plans in preparation to upgrade the capture system to an annual capacity of 100 kt. At the same time, R&D is being undertaken to improve the absorbent effectiveness of the MEA. The possibility of increasing the purity of the captured CO_2 to achieve the food grade standard (>99.99%) is also being assessed (Yang, 2011).

7.3 Guodian Corporation CO_2 capture and utilisation project

Following laboratory studies, the China Guodian Corporation is in the process of establishing a 20 kt/y CO_2 capture and utilisation industrial pilot plant at the Tianjin Beitang power plant. As with the examples described above, the captured CO_2 will be further treated to provide a food grade product for sale in Tianjin (MOST, 2010). The unit should be operational at the end of 2012 (MOST, 2011b).

7.4 The GreenGen IGCC/CCS project

The aim of the GreenGen project is to establish a high-efficiency, coal-based power generation system with hydrogen production through coal gasification, power generation from a combined-cycle gas turbine and fuel cells, and efficient treatment of pollutants with near-zero emissions of CO_2.

The GreenGen Company was formed in December 2005 to implement the project. The founding shareholders comprise China Huaneng Group, with a 52% share, together with the other four main power generation companies, China Datang Corporation, China Huadian Corporation, China Guodian Corporation, and China Power Investment Corporation; the two largest coal mining companies, Shenhua Group and China Coal Group, and the State Development and Investment Company, each of which holds a 6% share. GreenGen has sought international co-operation to take forward this project and, in December 2007, Peabody Energy of the USA took a 6% equity stake in the GreenGen Company.

The official plan is to design, build and operate the first 250 MWe IGCC power plant in China, to be followed within five years by an expansion to 650 MWe through the addition of a further 400 MWe, with the expectation that CO_2 capture will be included on the latter unit and the CO_2 used for EOR in the nearby Daquang Oilfield (GreenGen, 2008). On completion, the Project will generate 1690 GWe each year, which will be sold to the Northern China Power Grid Co through a 220 kilovolt (kV) transmission line. The Project will also sell about 117 million m^3 of syngas each year to the Tianjin Bohua Group for chemical production. In addition, waste heat from the power plant will be the main source of heat and steam to consumers located in the Harbour Industrial Park, which will further improve the overall process efficiency (Su, 2009).

The aim of Stage 1 of the overall project is to prove the scale-up of the Chinese gasifier design and to ensure overall reliability and acceptability of the integrated power plant. The 250 MWe IGCC power plant is being built in the Harbour Industrial Park of Tianjin City and, currently, is the only IGCC project in China that has progressed beyond the study phase, with construction approval having been received from the NDRC in 2009, Figure 10. Total construction costs are given as US$420 million, which will be covered by a $35 million loan from the Asian Development Bank (ADB), equity contributions of $84 million, a loan of $196 million from a group of local banks, and a $5 million grant from the ADB's climate change fund (PowergenWorldwide, 2010). The ADB has also provided a $1.25 million grant for technical assistance to build CCS capacity and to pave the way for the second and third phases of the programme, which are intended to lead to a scaled-up IGCC plant fitted with

Figure 10 Gasifier housing under construction in January 2010 at the 250 MWe IGCC near Tianjin City

CCS technology. The IGCC aspect of the GreenGen project was approved by MOST as a key scientific research programme in the eleventh Five-Year Plan period. It has also been approved by the Ministry of Environmental Protection.

From a technical standpoint, almost all the equipment will be built in China. The gas turbine will be a Siemens design to be built by the Shanghai Turbine Co – a Siemens-Shanghai Electric Co joint venture, with subsequent technology transfer into the joint venture already agreed. The gasifier will be a 2000 t/d, two-stage entrained flow TPRI design, which represents a considerable scale-up from the 36 t/d test unit for this Chinese technology. For sulphur recovery, the intention is to use the LO-CAT technology from the USA for which some of the equipment will be produced in China (Cao, 2009).

Construction of this IGCC plant is close to completion with system checks intended from late August 2011, to be followed by three months of commissioning. The exact duration of the subsequent R&D operational programme for the plant (rather than subsequent commercial power generation) is not yet finalised, being dependent in part on Hunaeng's financial situation and the level of Government support available.

For Phase 2, the aim is to improve the IGCC polygeneration (power-heat-syngas) technology, and to determine how best to take forward the fuel cell power generation technology, all leading to the design studies necessary for the intended GreenGen demonstration. A sidestream supply of syngas will be established together with an associated GreenGen laboratory. This will allow various techniques to be tested, which will include some syngas shift to produce hydrogen for fuel cell experiments. Such R&D will be supported by MOST. It is expected that there will be the capability to produce up to 30–60 kt/ CO_2/y, and that the larger-scale tests will include implementation of CO_2 EOR (Cao, 2011). The latter is subject to agreements being reached with one or more Chinese oil companies on EOR technology.

For Phase 3, the intention is that the consortium would scale up the power plant by building a 400 MWe IGCC, which should include hydrogen production based on coal, hydrogen-rich gas turbine power generation, CCS, fuel cell power generation and other key technology assessments, including the integration of the various product systems. The construction of this integrated demonstration scheme is now expected to start in 2015 and should be completed by the end of 2017, to be followed by operation and assessment until 2020. However, implementation of this phase of the project is entirely dependent on a financing mechanism being established such that Huaneng and the other partners are not financially disadvantaged by proceeding to demonstrate a technology that is as yet neither proven nor financially viable within the Chinese context.

7.5 Clean energy technology demonstration project in Lianyungang

The Energy Power Research Centre of the Chinese Academy of Sciences is leading on the design of a clean coal energy demonstration project in Jiangsu Province. This is intended to include a 1200 MWe IGCC power plant, which would also co-produce syngas and chemicals, with plans to incorporate CCS. The facility will be built alongside two 1300 MWe USC PC power plants and a 10 MW solar unit. It is intended to maximise heat integration between the IGCC, USC PCs and solar heat collector to further improve the efficiency of the system. It is also intended to demonstrate the capture of up to 1 Mt/y of CO_2 from these plants. The CO_2 would either be transported by 100 km pipeline to Binhai in the same province for injection into onshore deep saline formations, or be transported 200 km to the North Jiangsu oilfield for use in EOR projects (MOST, 2010).

It is understood that a pre-feasibility study has been completed and that the feasibility study will be completed in the latter part of 2011, with the plants expected to be operational by 2015, subject to government approval. However, it is difficult to reconcile these timescales with the technology status.

China has not yet proved the IGCC concept at the 250 MWe scale and no coal-based IGCC of 1200 MWe has been envisaged globally while the 1300 MWe USC PC power plant is at an early design stage. Given the NDRC's understandable caution regarding IGCC, it is questionable that such a project will be able to go forward within the declared timescale.

8 CCS in non-power coal gasification applications

As has been indicated, coal-fired power generation dominates coal use in China. However, in absolute terms, there is still a large amount of coal used in other industrial sectors, which include coking/iron and steel, cement, and chemicals via coal gasification (*see* Table 2, page 20). From a CCS perspective, for the coal-to-chemicals sector, there is a growth in scale and extent of application, with the opportunity to capture, at relatively low cost, concentrated streams of CO_2. These developments suggest a valuable potential for some early CCS demonstrations and commercial prototypes, probably for EOR applications.

8.1 Market development of coal gasification for synthetic oil, gas and chemicals production

China has a long history of coal gasification to produce fertilisers and some other chemicals. Until the mid-1990s, the approach was to have a network of small gasifiers spread over the populated regions of China to provide a local product. There were some 8000 of these small and environmentally unacceptable units, almost all of which were atmospheric pressure fixed bed systems with very low coal capacities (Xu, 2005).

However, since then, as part of China's industrial and economic reforms, there has been a growing introduction of large, pressurised oxygen-blown gasification units for chemicals production. Initially, these were built at various refineries to process petroleum residues to produce higher value products. However, this niche market has been rapidly superseded with the introduction of coal gasification for oil, gas and chemicals production. The driver for this change has been to establish a gasification-based coal transformation industry as a possible means to limit the use of oil and natural gas for production of transport fuels and a wide range of secondary chemical products (Minchener, 2011). However, for coal-to-oil transformation processes, there are major Government concerns regarding the excessive use of water as such plants would need to be established in the newer coalfields that are in arid regions of China, and the overall impact of a further massive increase in coal use should such technology be established on a commercial basis. Consequently, at present, the Government has effectively limited that programme to a major demonstration and several large-scale industrial trials. At the same time, it has allowed very large industrial scale demonstrations of coal to synthetic natural gas to proceed and for coal-to-chemical processes to be established. The two main chemical products are ammonia for fertiliser production, where significant economies of scale can be realised through the use of large modern gasifiers, and, more recently, methanol for the production of a wide range of secondary products, including olefins and DME.

The very great majority of the modern coal gasifiers in use in China are based on entrained flow designs, although there are a few fixed and fluidised bed units. Entrained flow gasification technology is favoured as it offers considerable fuel flexibility for the production of syngas, including the use of bituminous coals rather than anthracite in synthesis ammonia production. The scale of operation is significant, typically up to 2 kt coal throughput per day per unit (NETL, 2010).

Initially, the technology for these large gasifers was licensed from foreign suppliers with the current market leaders being GE and Shell, while Siemens, Lurgi-Sasol and U-Gas technologies have been introduced at a few sites. By the start of 2011, GE had issued some 47 licences for their gasification technology, of which ten sites were using oil residues and natural gas, with the remainder being coal applications. Shell had issued close to thirty licences, of which nineteen were for sites using coal.

However, increasingly, Chinese designs for pressurised entrained flow technology are becoming available. Much of the fundamental understanding and the subsequent technology development

Table 4 Overview of national (973) basic research programme for gasification in China (973.com, 2011)

Project	Lead participant
Basic research of coal pyrolysis, gasification and high temperature purification process	Taiyuan University of Technology
Basic research of efficient large-scale entrained flow gasification technology	East China University of Science and Technology
Basic research of large-scale efficient and clean gasification of coal and other carbon solid material	East China University of Science and Technology
Basic research of polygeneration applications using coal gasification gas and pyrolysis coal gas to produce synthesis gas	Taiyuan University of Technology

Table 5 Overview of national high technology (863) gasifier development programme in China (Xiao, 20007)

Project	Lead participant
Novel coal water slurry (CWS) coal gasification technology	Yankuang Group
Two-stage dry pulverised coal pressurised gasification	Thermal Power Research Institute (TPRI)
Non-slag/slag two-stage coal gasifier	Tsinghua University
Production of syngas with cogasification of coal and natural gas	Institute of Process Engineering, CAS
Novel high temperature coal gas cleaning technology	Coal Research Institute
Design for IGCC power station	TPRI
R&D of polygeneration system based coal gasification	Yankuang Group

Table 6 Status of non-power coal gasification projects in China (Zhang, 2011)

Technology supplier	Coal gasification projects		
	Operational	Design/ construction	Total
GE	27	10	37
Shell	14	5	19
Siemens	1	2	3
Sasol Lurgi	3	3	6
U-Gas	1	1	2
ECUST	8	9	17
TPRI	–	3	3
CACG	3	15	18
Tsinghua U	3	5	8
ICC-CAS	3	–	3
Total	63	53	116

activities were supported by the MOST 973 and 863 R&D programmes respectively (Cai, 2010), as indicated in Tables 4 and 5. These were followed from 2005 onwards by various demonstrations and commercial implementation of gasification for non-power applications.

Of these options, since 2005, the ECUST multi-nozzle opposed burner CWS gasifier has become rapidly established at scales comparable to many of the international technologies. (NETL 2010, Cai 2010).

The current situation for both international and domestic coal gasifiers in China is summarised in Table 6. This indicates the number of projects that are either operational or at the contracted design/construction stage. It is stressed that, for many projects, there will be several large gasifiers installed at a particular site. For example, the Shenhua Baotou plant has an annual production capacity of 1.8 Mt of methanol, which is then converted to some 600,000 t of polyethylene and polypropylene, Figure 11. It includes five operational GE gasifers plus two spare units.

Figure 11 The Shenhua Baotou coal-to-olefins plant (Zhang, 2011)

Following this surge of interest by Chinese chemical companies in domestic-based technology, GE has countered by increasing the size range of its units to include a gasifer with a coal throughput of ~3 kt/d and syngas (H_2 + CO) production of ~210,000 m^3/h. The driver is to enable end-users to reduce capital and operating costs by decreasing the number of gasification trains required for the large coal-to-chemical projects (GE Energy, 2009). It has also agreed to form an industrial coal gasification joint venture with the Shenhua Group to combine their respective expertise in industrial gasification technologies and coal-fired power generation (Pennenergy, 2011). The intention is for GE and Shenhua to sell industrial coal gasification technology licences, jointly develop IGCC projects, and to undertake R&D to make the technology more attractive on a commercial basis.

Shortly after the GE collaborative arrangement was made public, Shell announced that it had agreed to collaborate with the Wison Group of Shanghai in the design and marketing of their gasification technology (The Hydrogen Journal, 2011). This will include the joint development of a hybrid gasification technology, combining Shell's design with state-of-the-art bottom-water quench technology. This approach should result in a simplified design at lower cost that should prove suitable for a wider range of coal feedstocks, which could be more competitive in the Chinese market (E&P, 2011).

8.2 Chemical product issues

The syngas produced in the gasifier is primarily CO and H_2. This can be processed to make various products, of which the two key ones are ammonia and methanol (Fernando, 2008). For ammonia production, any impurities in the raw syngas must be removed, after which it is desulphurised. The near-sulphur free syngas is then passed to a shift reactor where the CO component is reacted with steam over a catalyst in order to produce H_2 and CO_2, based on the following reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

The H_2 and CO_2 gases can then be readily separated using either a physical or chemical solvent (often the same one as used for the desulphurisation step). The H_2 can be used either directly as a fuel or reacted with nitrogen to produce ammonia. The latter requires a hydrogen to nitrogen ratio of 3:1 and nitrogen from the air separation plant can be utilised as the source of nitrogen. The high pressures used in entrained flow gasifiers are advantageous for ammonia production. Once produced, the ammonia can be further reacted with some of the CO_2 to form urea.

For methanol production there are numerous reaction schemes based on the following reactions (Inouye and others 2008):

$$CO + 2H_2 \rightarrow CH_3OH$$

$$CO_2 + H_2 \rightarrow CO + H_2O$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

The optimised syngas specification for methanol production is a H_2: CO molar ratio of 2. For a typical syngas composition as produced in a coal gasifier, a partial 50% shift is required to be followed by CO_2 removal. As in the case of manufacturing ammonia, it is necessary to choose the most suitable pressure, syngas cooling arrangement and acid gas removal system. Unlike ammonia production where an O_2 purity of 95% can be tolerated, for methanol production, the presence of nitrogen in the syngas is undesirable; hence, an O_2 purity of 99.5% is necessary (Higman and Van der Burgt, 2003).

In each case, the amount of CO_2 that is unused will depend on the overall chemicals process scheme. For example, if H_2 is the sole end product then all of the CO_2 produced has no use within the overall process. However, if ammonia is a product and that is then integrated into an urea plant, then some of the CO_2 will be reacted with ammonia to produce urea. For methanol production, since only partial shift of the syngas is required, then a significant proportion of the CO will not be converted to CO_2. Currently, in almost every plant irrespective of the end product, any concentrated CO_2 stream that is not used in the overall process scheme is vented to atmosphere, usually because the plant operator cannot find a guaranteed market for it.

8.3 CO_2 capture opportunities

From a CCS perspective, these modern gasifiers in China represent reasonably large stationary point sources of high concentration CO_2 gas streams, these being produced as a necessary consequence of the chemicals production processes. Depending on the size and number of gasifiers in operation, the annual quantity of CO_2 released at a site ranges from about 0.5 Mt to well over 2 Mt. Tables A1 to A8 in the annex to this report provide key data on these modern coal gasifiers, with information on the units that use either refinery residues or natural gas as feedstocks also provided for completeness. Each table provides a list of non-power coal gasification plants in China on a licensor basis, both operational and under contracted design/construction. On the basis that the plant will operate at full capacity, the following information has been included where it has been found to be publicly available:

- owner, application and location;
- type of feedstock and throughput;
- syngas production rate;
- type and mass of end products;
- mass of CO_2 produced;
- status (ie operational or at design construction stage).

The estimate that has been made on the mass of CO_2 that could be available from each coal-to-chemicals site, is on the same basis as that used in preliminary work undertaken as part of a China-USA collaborative study, as reported in Chapter 9 (Meng and others, 2005; Dahowski and others, 2009). The annual cumulative emissions from these modern coal gasifiers, for projects either operational or at the contracted design/construction stage, would be over 100 Mt. With the growing numbers of projects, the numbers of the larger point sources of CO_2 are likely to continue to increase in the near future. There have been some speculative projections that assume a massive upturn in coal transformation projects, which suggest annual CO_2 emissions could be 300 to 350 Mt by 2020 (Aden and others, 2009). However, this would depend on the introduction of positive policies to encourage such a growth in this sector, and at present the NDRC is adopting a cautious approach due to concerns about resource utilisation and the overall economics of some of the processes (Minchener, 2011).

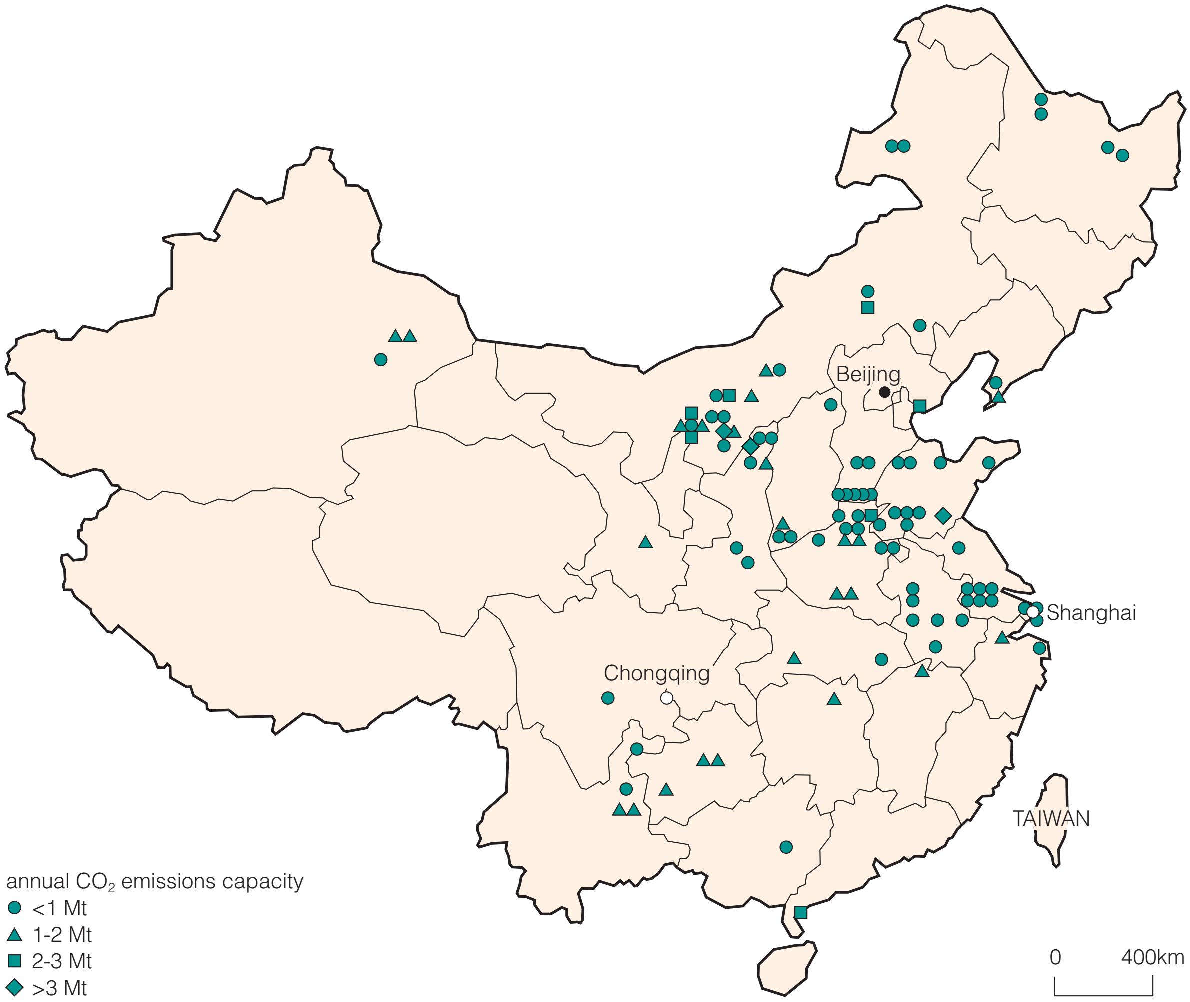

Figure 12 Geographical representation of likely CO_2 emissions from modern coal to chemicals plants in China

Nevertheless, the attraction of demonstrating CCS on such gasifiers is that the results would be applicable to the overall development of the technology for many coal using sectors and projects could be undertaken at significantly lower costs compared to operations on a coal-fired power plant. This is because the CO_2 is already produced as a concentrated stream and so the CCS marginal costs are essentially those of CO_2 compression, transport and injection, which are much lower than those where CO_2 capture also has to be included (Meng and others, 2007, Dahowski and others, 2009). Equally importantly, many of these individual gasification projects are located quite close to one another within industrial zones. Figure 12 provides a geographical representation of the locations of each modern coal-to-chemicals plant (either operational or at the contracted design/construction stage) including an estimate of annual CO_2 emissions, assuming each plant operates at design capacity. This shows that many of these units are already large (>1 Mt/y) or very large (>2 Mt/y) CO_2 emitters. In various provinces (especially Inner Mongolia, Ningxia, Shaanxi, Henan and Shandong) there are growing clusters of units being established that are emitting levels of CO_2 equivalent to that from a large power plant.

This offers the prospect of establishing a CCS network, which would comprise a shared or interconnected system for transporting CO_2 from multiple capture sources to one or more underground injection sites. Such networks should offer economies of scale and hence lower overall transport and (potentially lower) storage costs compared to an unintegrated single-source-single-storage project (Hegan, 2011). For example, a study looking at establishing a CCS network in the UK estimated cost savings of 33% over the longer-term compared to individual pipelines from each emitter to their respective storage site. In addition, a co-ordinated regional effort to establish a network can reduce not only costs but also the risks for both initial and future projects since an established network would reduce the barriers of entry for subsequent projects, by offering access to existing infrastructure while also providing established expertise and business and financing structures (CO_2Sense Yorkshire, 2010).

At the same time, when a network is first established there are some additional risks for the first movers. There is an investment risk with over-sizing infrastructure based on anticipated but uncertain demand in the future; technical risk from inter-operability issues associated with handling multiple sources of CO_2; commercial risks with participation of multiple stakeholders; storage risk in ensuring sufficient capacity to handle the large CO_2 volumes over time; and regulatory risks if future regulatory developments are inconsistent with the network's design (CO_2Sense Yorkshire, 2010).

There are also some technical considerations. Recent work suggests a potential trade-off between the use of very high pressure pipelines to transfer very pure CO_2 in a supercritical state for EOR applications and future CCS pipelines where the CO_2 will contain some level of impurities (Seevam and others, 2008). The type and quantity of impurities will depend on the capture technology used, the storage option and also an economic balance between clean-up and transport costs. Such impurities would affect many aspects of CO_2 pipeline transportation, especially the determination of the optimum operating pressures, pipeline sizing, re-pressurisation distance, number of pumps and also their power requirements. In general, impurities would reduce pipeline capacity and this may be an issue in a pipeline network due to the presence of multiple sources of anthropogenic CO_2.

8.4 CO_2 purity issues

The downstream syngas processing system (water-gas shift, sulphur capture, CO_2 removal) determines the quality of the CO_2 stream (Adams and Bonnell, 2009), irrespective of the coal gasifier technologies being installed. The purity needs for CO_2 are determined by the process scheme requirements and there is a balance to be reached between limiting the processing costs and avoiding the loss of valuable gas components such as CO and H_2 in the CO_2 waste stream. In overall terms, the higher the quality of the CO_2 specification, the greater the processing costs.

Such syngas processing systems are sold to the Chinese enterprises by a range of international

Table 7 Typical composition of the CO_2 stream following pre-combustion capture and separation (Santos 2011, Palla 2010)

Gas component	Selexol standard gas cleaning	Selexol new gas cleaning	Rectisol gas cleaning
CO_2, %	97.95	99.7	99.7
H_2, %	1.0		20 ppm
N_2, %	0.9		0.2
Ar, ppm	300		150
Sulphur compounds, ppm	100	2	20
CO, ppm	400	100	400
CH_4, ppm	100		100
Methanol, ppm			200
H_2O*, ppm	600		10

* almost all of the H_2O would be separated during compression

technology suppliers and consequently gas qualities will be comparable to those for coal gasifiers in other countries that use modern techniques. Table 7 provides typical gas compositions arising from the use of various gas cleaning and processing systems (Santos, 2011; Palla, 2010).

Should the separated CO_2 be used in EOR applications, then the CO_2 purity must be at least 96%, which can readily be achieved by the gas cleaning systems, as shown in Table 7. For storage in a saline aquifer, it could perhaps be of a lower purity. Studies are under way to establish the optimal conditions with regard to CO_2 purity under which capture, transportation, long-term storage and EOR can be implemented (Carbon Capture Journal, 2010a).

8.5 Chinese CCS demonstration initiatives in this sector

The first major non-power trial of CCS in China is underway at the Shenhua Direct Coal to Liquids (CTL) Demonstration Plant, close to Erdos, Inner Mongolia Autonomous Region (Xinhuanet, 2010). That plant includes two Shell coal-fuelled gasification units to produce syngas (ie CO and H_2), after which there is a shift reactor where steam reacts with the CO to convert the syngas to a much higher concentration of H_2 and CO_2. On a weight basis, the resulting gas mixture contains about 87% CO_2 which means the H_2 can be separated from the CO_2 at comparatively low cost. The hydrogen is used in the hydrogenation process to produce synthetic oil while the CO_2 would normally be emitted to atmosphere. For every 1 t of synthetic oil produced by the direct coal liquefaction process, close to 3 tCO_2 would be released (Capture Ready, 2010a).

As part of China's first integrated CCS industrial-scale trial, some of this CO_2 is diverted via a sidestream, treated, and compressed to give a 99.2% pure liquid. This cryogenic liquid is then transported by road tanker to a location 17 km away from the demonstration plant, where it is injected at a pressure of 35–40 MPa through one injection well into a saline aquifer some 2–3 km below ground, Figure 13. There is also an additional well for monitoring activities. The storage site is in a desert region (Capture Ready, 2011a). CO_2 injection started in January 2011 and is scheduled to continue until June 2014, by which time some 300 $ktCO_2$ are expected to be stored (MOST, 2011b). Results are not yet readily available regarding the ability to achieve the target 100 kt/y injection rate (Bo, 2011).

Figure 13 Storage vessels at the Shenhua CCS industrial pilot site (MOST, 2011b)

The design and construction of the injection and storage site was undertaken by Petro China. Construction took about seven months at a capital cost of RMB210 million (US$31 million). Subject to satisfactory operation of the CTL plant, the Shenhua Group has estimated that the operational cost to capture and store the CO_2 will be close to 50 US$/t (Chinacsr, 2010).

Shenhua is also conducting a feasibility study into a second facility that will be capable of handling 1 Mt of CO_2 annually and there are plans to develop a larger facility capable of handling 3 Mt annually. However, in both cases, no schedule for construction has been set.

9 International co-operation

There are many, varied types of co-operation on CCS between China and other countries, including:

- membership of international organisations;
- bilateral agreements;
- multilateral agreements;
- academic co-operation, with financial support from various funding bodies;
- industrial co-operation, either with or without government financial support.

Where the co-operation includes CCS R& D, such projects run in parallel to the national programme, which is the responsibility of MOST. These projects are primarily undertaken by research organisations on both sides, although there is industrial participation in some cases. Where such work might develop to the point where commercial prototype demonstration projects are being considered, then this falls within the remit of the NDRC.

9.1 Collaboration through international organisations

China is a member of a number of international cooperative organisations, which are concerned, in part, with CCS. Thus:

- MOST is the Chinese Government representative for the GCCSI, which aims to help deliver the G8's goal, agreed in July 2008, of developing at least 20 fully-integrated industrial-scale demonstration projects around the world, to accelerate the broad deployment of CCS technology by 2020. The Huaneng Group has signed up as the representative of the Chinese power industry and the China Steel Corporation is also a member with a focus on non-power CCS applications.
- MOST is also the Chinese representative for the Carbon Sequestration Leadership Forum, which is an international climate change initiative that is focused on the development of improved cost-effective technologies for the separation and capture of CO_2 for its transport and long-term safe storage (CSLF, 2011). This includes addressing key technical, economic, and environmental obstacles through promotion of awareness and the championing of legal, regulatory, financial, and institutional environments conducive to such technologies.
- The Chinese Government was part of the Asia-Pacific Partnership on Clean Development and Climate (APP), which was a voluntary partnership among seven major Asia-Pacific countries, namely Australia, Canada, China, India, Japan, Korea, and the USA. These countries worked together to address increased energy needs and the associated issues of air pollution, energy security, and climate change. While the APP has now formally ended, some of these projects are continuing via various bilateral arrangements.
- The Huaneng Group, is a shareholder and partner of the FutureGen Alliance, which is a public-private partnership to build a first-of-its-kind coal-fuelled, near-zero emissions demonstration power plant.

9.2 R&D related activities

The nature of the challenges facing CCS means that many of the R&D projects that have been established comprise several types of activities, such as technology development, CO_2 storage characterisation, impact modelling together with policy/regulatory studies. In many cases, there is a considerable element of capacity building. The projects are grouped on a nation-by-nation basis.

9.2.1 China-Australia co-operation

Australia and China have established a range of CCS collaborative activities. These have been undertaken either as part of both countries' commitments to the APP or through the China-Australia Joint Coordination Group on Clean Coal Technology (JCG).

Under the APP, these bilateral projects included co-operation between CSIRO and the Huaneng Group to establish the CO_2 capture sidestream on the coal power plant in Beijing (*see* Chapter 7), together with the China-Australia Geological Storage of CO_2 (CAGS) project, collaboration on post-combustion capture and on enhanced coalbed methane (ECBM) projects, which are described below. While the APP has now formally ended, many of these projects are continuing, with the intention to incorporate such work within the JCG framework.

The JCG was established in 2007 to facilitate and enhance the development, application and transfer of low emissions coal technology. It is supported financially by the Australian Government through the Department of Resources, Energy and Tourism (RET), which is working closely with China's NEA. The scope of work includes research, for which contracts were finalised in early 2011 to cover six collaborative projects on various aspects of CCS, together with larger-scale development activities.

China-Australia geological storage of CO_2 programme

The China Australia Geological Storage of CO_2 (CAGS) Project is a collaborative venture that aims to help accelerate the development and deployment of geological storage of CO_2 in China and Australia (CAGS, 2011). It includes knowledge sharing through several phases, such as data collection, study-module development, training and implementation and site-specific assessment. It is funded by the Department of Resources, Energy and Tourism of Australia through the Asia-Pacific Partnership on Clean Development and Climate. The lead partners from Australia and China are Geosciences Australia and ACCA21 respectively while the Chinese partners include various institutes of the CAS, the China University of Petroleum, Tsinghua University and the MEP.

The projects include:

- Site Selection Methodology and Criteria for CO_2 Geological Storage, which aims to develop a new methodology for CO_2 storage in Chinese sedimentary basins. The research work includes the definition of site selection steps, development of selection methodology and criteria, and a case study in the Liaohe oilfield.
- Selection Criteria for Oil/Gas Reservoirs for CO_2 EOR and Geological Storage, which intends to develop selection criteria for oil/gas reservoirs for CO_2 EOR and storage, including geological characteristics, oil/gas reservoirs characteristics, oil/water/CO_2 properties in the reservoir and CO_2/water/rock interaction. This is being undertaken at the Liaohe oilfield.
- Environmental Impact and Risk Management, which intends to produce policy recommendations for environmental impact assessment and risk management of CO_2 storage.

China United Coal bed Methane Corporation-(CSIRO)

The China United Coalbed Methane Corporation (CUCBM) is a state-owned company, established with rights to explore, develop and product coalbed methane (CBM) in co-operation with overseas companies, and in July 2010 it was announced that Australia's CSIRO had teamed up with CUCBM on a US$8.5 million underground CO_2 storage project in China's Shanxi Province. The pilot project will store 2 ktCO_2 underground and extract methane as a fuel source. While the project will focus on advancing enhanced CBM recovery, it will also progress the transport and storage aspects of CCS.

Feasibility study for a commercial-scale CCS project

In December 2010, China's NEA signed a Memorandum of Understanding (MoU) with RET to collaborate on a feasibility study for a full-scale CCS project in China. This will draw on $12 million committed under the JCG, and focus on the demonstration of integrated post-combustion capture and storage for a commercial-scale (600 MWe) coal power plant. Work on the project is currently under way with an initial scoping study being undertaken by Australia's CSIRO and China's Clean Energy Research Institute (Capture Ready, 2010b).

9.2.2 China-Canada co-operation

Under a bilateral MoU, clean energy, especially the cleaner use of coal including CCS, has been identified as the key area for potential co-operation between the two countries.

CO_2 injection/storage in deep coal seams for coalbed methane exploitation

There has been a coalbed methane (CBM) technology development project agreement between China and Canada since 2002 (Gassnova, 2010). The initial work to end 2006 by CUCBM and the Alberta Research Council focused on a micro-pilot field test of a shallow coal seam with single well injection in the South Qinshui Basin, near Jincheng City, Shanxi Province. From a CCS perspective, the value of that work is questionable. However, a second phase began in January 2008, which might have more relevance to CO_2 storage. This focuses on the development of technology for CO_2 injection in deep unmineable coal seams for CO_2 enhanced CBM and to allow for geological storage. The partners are CUCBM, Petromin and EnviroEnergy. This RMB10 million, five-year project comprises two phases: a single well injection pilot test in deep coal seams to be followed by multi-well pilot testing. All work is being undertaken in the north block of Shizhuang of the Qinshui Basin. That said, it is understood that coal seams in the region comprise prime anthracite and that the intended well depths are such that coal mining is very possible.

9.2.3 China-EU co-operation

There has been a very significant CCS co-operation between EU nations and China, within the China-EU NZEC Agreement, announced as part of the EU-China Partnership on Climate Change at the EU-China Summit in September 2005. In this, the parties agreed '*to develop and demonstrate in China and the EU advanced, near-zero emissions coal (NZEC) technology through carbon capture and storage*' by 2020 (Europa, 2005). Two MoUs were signed with MOST, one by the UK Government in December 2005 and one by the European Commission (EC) in February 2006. These had identical aims and objectives. Thus, three phases of co-operation were envisaged, with:
Phase 1: Exploring the options for NZEC technology through CCS in China;
Phase 2: Defining and designing a demonstration project;
Phase 3: Construction and operation of a demonstration project.

China-UK NZEC Initiative

As a result of the MOST-UK Government Agreement, the China-UK NZEC Initiative was launched in November 2007, with a budget of some £3 million for Phase 1, with completion by October 2009 (NZEC, 2009a,b). This was a significant capacity-building project, which was undertaken by nineteen Chinese and nine UK partners, including universities, institutes and industry.

The aim was to determine:
- the trends of energy use in China and the implications for use of CCS;
- the options for CCS in China;
- the more appropriate means to capture CO_2 from power plants;
- the better CO_2 storage options in China;
- the costs of CCS;
- the policy and regulatory issues that would affect the use of CCS.

The contracted partners and associated organisations who participated either in the R&D programme or as hosts for Chinese students to undertake CCS related studies in the UK were The Administrative Centre for China's Agenda 21; AEA Technology; Alstom Power; 3E Research Institute of Tsinghua

University; BP Clean Energy Research & Education Centre of Tsinghua University; British Geological Survey; British Petroleum; Cambridge University; China United Coalbed Methane Corporation; China University of Petroleum of Beijing; China University of Petroleum of Huadong; Chinese Academy of Sciences; Cranfield University; Department of Environmental Sciences & Engineering of Tsinghua University; Department of Chemical Engineering of Tsinghua University; Department of Thermal Engineering of Tsinghua University; Doosan Babcock; Edinburgh University; Energy Research Institute; GreenGen Corporation; Heriot Watt University; Imperial College; Institute of Engineering Thermophysics of the CAS; Institute of Policy & Management of the CAS; North China Electric Power University; Schlumberger; Shell; Thermal Power Research Institute; Wuhan University and Zhejiang University.

The China-EU COACH project

The UK NZEC Initiative was complemented by the China-EC COACH project (COACH, 2009). This was a three-year project, with a €6 million budget, part funded by the EC FP6 programme, that began in late 2006. There were 12 EU partners and eight Chinese partners, including IFP, Sintef, Geus, BGS, KTH, BP, StatoilHydro, Shell, Schlumberger, Alstom, Air Liquide, Atanor, ACCA21, Tsinghua University, Zhejiang University, Institute of Engineering Thermophysics, Thermal Power Research Institute, Institute of Geology and Geophysics, RIPED and Huaneng for the GreenGen Consortium.

This project focused on CCS with polygeneration in China, with the aim to prepare for implementation of large-scale clean coal power stations with CO_2 capture together with provision for EOR using CO_2 injection. The work programme included:

- enhancement of knowledge sharing and capacity building;
- preparation for the implementation of large scale clean coal energy facilities by 2020;
- addressing of the cross-cutting issues, for example Legal, regulatory, funding and economic issues;
- identification of reliable geological storage capabilities for CO_2 in China.

The GEOCAPACITY and STRACO2 projects

The European Commission also funded the GEOCAPACITY project, working on CO_2 storage assessment, and STRACO2, to consider CCS regulatory requirements, in the EU and China.

The GEOCAPACITY project comprised some CO_2 storage assessment work both in Europe and China on a consistent basis (GEOCAPACITY, 2009). The primary aim of the STRACO2 project was to support the ongoing development of a comprehensive regulatory framework for commercial applications of CCS in Europe. At the same time, recognising the great potential for CCS in China, the secondary aim was to increase EU-China S&T co-operation on regulatory development. The approach was to establish the EU regulatory framework as the basis for dialogue and priority setting with regulatory authorities in China with a view to further joint activities (STRACO2, 2009).

NZEC next steps

In June 2009, the European Commission set out plans for establishing an investment scheme to finance the joint China-EU design and construction of a demonstration-scale CCS power plant in China (Europa, 2009a), which provided the means to move forward the NZEC project. The Commission allocated funding of up to €50 million for the construction and operations phase of the project, out of a total of €60 million that had been earmarked for co-operation with emerging economies on cleaner coal technologies and CCS. Depending on the choice of technology used, the additional cost of constructing and operating over 25 years a new power plant equipped with CCS in China has been estimated at €300–550 million (Gassnova, 2010).

This was followed, in November of that year, with the signing of a MoU by MOST and the EC, which initiated Phase 2 of the overall co-operation programme (Europa, 2009b). Both sides agreed that there should be two further phases under the China-EU NZEC agreement leading to the collaborative demonstration project in China. Phase 2 should comprise two parts. Phase 2A should provide an objective assessment of various CCS demonstration options from which the most suitable choice can be made. For Phase 2B, the design of the demonstration project, including a FEED study of the chosen option should be implemented. Phase 3 should be the construction and operation of a CCS demonstration plant in China. Both parties agreed that it is also important to ensure that the research initiatives are taken further to build on the NZEC results, enhancing scientific and technical capacity, such that any demonstration would form an integral part of the development of a CCS strategy for China.

Subject to contract, funding for Phase 2 will be provided by Norway and the UK, with the former covering all the costs of Phase 2A and much of 2B, and the UK seeking to provide the balance for 2B.

Chinese participation in other EC framework projects

In addition, some Chinese organisations have strengthened collaboration on CCS by participating with EU partners in other EC FP projects that were focused on various aspects of the CCS chain even though there was not a specific link to China. These included:

- the inclusion of the Research Institute of Petroleum Exploration and Development of PetroChina (RIPED) and the China United Coalbed Methane Company (CUCBM) in MOVECBM, an enhanced coalbed methane study, which finished late in 2008 (Movecbm, 2009). The objective was to improve understanding of CO_2 injection into coal seams and the migration of methane, thus ensuring long-term reliable and safe storage. The work programme comprised modelling and laboratory work, with links to the test site in Kaniów, Poland, previously investigated by the EC RECOPOL project;
- Dalian Institute of Chemical Physics in the CACHET (pre-combustion CO_2 capture R&D) project (Cachet, 2009);
- Tsinghua University in the CAPRICE (CO_2 capture using amine processes) project (Caprice, 2009).

9.2.4 China-Italy co-operation

In May 2008, MOST and the Ministry of Environment of Italy signed a MoU whereby ENEL will work with Chinese enterprises to co-operate on clean coal, CCS and USC coal power plant (Benelli, 2010). As well as a series of information exchanges, in 2010 this led to a two-phase agreement to develop a feasibility study for CCS integration on a Chinese coal-fired power station. In Phase 1, which will last for 18 months, the partners will consider a demonstration-scale activity incorporating CO_2 capture, transport and injection for EOR applications. Subject to both sides agreeing to continue co-operation, this will be followed by Phase 2, of two years duration, which will include:

- the development of a front end engineering design for adding CCS EOR to the nominated coal-fired power plant;
- a detailed project plan and budget estimate for this demonstration near-zero emission coal-fired plant.

9.2.5 China-Japan industrial scale CCS co-operation

As part of a much larger scale development, in May 2008, Japan and China announced their intention to jointly develop a CCS and EOR project which aims to recover 3–4 Mt of CO_2 each year from two coal-fired power plants in China. This major industrial project will be located in Heilongjiang Province in North-East China, 100 km from the Daqing oilfield.

The Japanese partners, under the Ministry of Economy, Trade and Industry (METI), include the JGC Corporation (a partner in the Algerian In Salah CCS project), Japan Coal Energy Centre, Toyota Motors, Mitsubishi and the Research Institute of Innovative Technology for the Earth. For China, the NDRC is the lead government department with input from PetroChina, Daqing Oil Field Ltd, Harbin district government, Harbin Utilities Company and China Huadian Corporation (Webb, 2008).The research and design development phase was due to have started in 2009, with both Japanese and Chinese power and coal industry investments, and was expected to be completed by end 2011. Both sides had agreed to provide funding of US$300 million, allocating US$100 million per year for each year of the project. It is understood that Japan was to be responsible for developing the power-generation, CO_2 capture and transportation aspects, while China was to address CO_2 storage and enhanced oil recovery (Reuters, 2008). The intention was to use two 600 MWe coal-fired power plants, retrofitted for post-combustion CCS and linked by pipeline to a nearby mature oilfield to enhance oil production by 30–40,000 barrels per day (bbl/d). The reason for using two power plants was to spread the 10–15% energy penalty associated with CO_2 capture and so limit local electricity supply disruptions. Based on initial tests in China, the partners believed that it would be possible to achieve a CO_2-to-oil recovery ratio of 2:1. Since the initial announcement, there has been very limited additional information made available and as such the status is unclear.

9.2.6 China-Norway co-operation

In addition to offering to financially underwrite Phase 2 of the China-EU Near-Zero Emissions Project, Norway is likely to undertake further co-operative ventures through their joint framework agreement for Co-operation and Dialogue on Climate Change (Gassnova, 2010). This new co-operation programme will give priority to research on climate, climate technology. Under the technological aspect this can include activities on CCS in fossil fuel based power generation and industrial point source emissions. The programme is managed by Gassnova in co-operation with the Research Council of Norway.

9.2.7 China-UK co-operation

This includes direct and indirect government funded R&D together with some private sector co-operative actions. A major part of this work has been the NZEC Initiative, which is reported under the China-EU heading.

EPSRC and the Natural Science Foundation of China

At the academic level, there is continuing co-operation between the UK and China via the Engineering and Physical Sciences Research Council (EPSRC) and the Natural Science Foundation of China, covering Renewables, Cleaner Fossil Fuels and most recently CCS. For CCS, the aim is to establish new and innovative collaborative projects covering (EPSRC 2010a,b):

- simulation and modelling of capture and transport;
- predicting and monitoring reservoir response;
- CCS potential and pipeline network optimisation;
- solvent based post-combustion capture;
- CO_2 physical properties and flow metering.

Current projects include R&D on:

- the next generation of activated carbon adsorbents for the pre-combustion capture of CO_2;
- novel catalytic membrane micro-reactors for CO_2 capture via pre-combustion decarbonisation;
- multiscale evaluation of advanced technologies for capturing the CO_2 (for example, chemical looping applied to solid fuels);
- fundamental study of migration of supercritical carbon dioxide in porous media under conditions of saline aquifers;
- fundamentals of optimised capture using solids.

Chinese advanced power pant carbon capture options

The UK has established further co-operation with China via the CAPPCCO project (DECC, 2011). Thus DECC, in collaboration with MOST, are sponsoring some information-gathering activities in

China pertinent to the CCS ready concept. The aim is to develop and define options for integrating CO_2 capture plant with advanced Chinese PC power plants to allow a rapid transition to a high level of CO_2 emissions reduction. A key activity is to identify and engage with key stakeholders to ensure that relevant information transfer takes place. The partners include Alstom Power; Datang International Power Generation Co Ltd; Doosan Babcock; Harbin Boiler Company Limited; Harbin Institute of Technology; National Power Plant Combustion Engineering Technology Centre; University of Cambridge; University of Edinburgh; Xian Jiaotong University and Yuanbaoshan Power Plant.

Carbon capture and storage readiness in Guangdong Province

On a broader, strategic level, the UK Foreign and Commonwealth Office together with the GCCSI are funding a feasibility study of Carbon Capture and Storage Readiness in Guangdong Province (GDCCSR). This is led by the South China Sea Institute of Oceanology (CAS), in partnership with the Energy Research Institute of the NDRC; Guangzhou Institute of Energy Conversion; Linkschina Investment Advisory Co Ltd; University of Cambridge; University of Edinburgh; and the Wuhan Institute of Rock and Soil Mechanics. This capacity-building project will:

- assess the theoretical CO_2 storage capacity of geological formations in Guangdong Province and the northern region of the South China Sea;
- analyse current and planned CO_2 point sources in Guangdong, with subsequent sources-to-sinks mapping together with an economic analysis of the costs and benefits of CCS (with and without CCS-Readiness) to Guangdong under different policy scenarios;
- create a China Low-Carbon Energy Action Network (CLEAN) as a non-government and not-for-profit organisation linking businesses with policy makers and academics to support China's low carbon development by providing a communication and co-operation platform to promote the generation and transfer of knowledge related to research, development and deployment of CCS and CCSR in South China;
- develop pre-feasibility analysis studies for two pilot CCS-ready installations in Guangdong;
- provide policy recommendations for integration into the Guangdong Low Carbon Development Roadmap.

BP-Tsinghua University Clean Energy Research and Education Centre

In addition, from the private sector, BP and Tsinghua University established the BP Tsinghua University Clean Energy Research and Education Centre, which was launched in July 2003. It aims to combine the strengths to create a world-leading institute for energy strategy study for China. The researchers have the academic freedom to pursue any aspects of clean energy policy or strategy that appears attractive to China (BP, 2003).

BP-CAS Clean Energy Commercialisation Centre

BP and the Chinese Academy of Sciences have established a Clean Energy Commercialisation Centre (CECC) joint venture. The aim is to integrate individual clean energy related technologies – coal gasification, coal-to-liquids, coal-to-chemicals, CCS, coalbed methane and underground gasification – from CAS institutes and other organisations both within and outside of China, into competitive integrated feedstock manufacturing and product distribution systems and solutions (CAS, 2008).

9.2.8 China-US co-operation

China and the USA have established a series of CCS related initiatives.

US-China Clean Energy Research Centre

In November 2009, China and the USA launched the Clean Energy Research Centre (CERC) in order to facilitate joint research, development, and commercialisation of clean energy technologies (PowergenWorldwide, 2009). The Joint Work Plan, which is expected to accelerate the development and deployment of clean coal technology with CCS in both countries, was approved in January 2011 (PowergenWorldwide, 2011a). It aims to address technology and practices for clean coal utilisation, including carbon capture, utilisation and storage. The research teams, which comprise universities, institutes, non-government organisations and industry, are led by Huazhong University of Science and Technology and West Virginia University for China and the USA respectively. The Centre is being established in Optical Valley of Wuhan, China (CaptureReady, 2011b).

The key topics include:

- IGCC with CCS, to establish robust, transparent cost and performance estimates for this class of power plant, together with pilot testing leading to development/demonstration opportunities;
- post-combustion CO_2 capture, utilisation and storage technology, to examine competing technology pathways (for example amines and chilled ammonia) for cost, ease of engineering retrofit, energy and environmental performance;
- storage capacity and near-term opportunities, to improve understanding and provide verification of key technologies for CO_2 storage in saline formations;
- CO_2-algae bio-fixation and use, to establish the basis for a demonstration by addressing the detailed process of utilising power plant flue gas, post processing, and the utilisation of the algal biomass from the process to produce multiple products;
- oxyfiring combustion, to establish cost and performance breakthroughs for this potential technology through research, development and demonstration;
- coal cogeneration with CO_2 capture, to focus on the research and development of new systems with combined pyrolysis, gasification, and combustion, and new CO_2 capture processes.

Fundamental studies of CO_2 storage in aquifers

As part of its Global Climate and Energy Project, Stanford University has established international collaboration with Chinese Universities to address fundamental issues associated with large-scale storage of CO_2 in saline aquifers in China (Stanford University, 2011). Partners include the China University of Geosciences at Wuhan; Peking University; and the University of Southern California. The project integrates geological modelling, reservoir simulation and laboratory experiments to identify the best scientific approach for developing safe and secure methods for storage of CO_2. The early stage of this particular co-operation assisted the Shenhua Group in establishing its initiative to demonstrate CO_2 capture and subsequent aquifer storage at its coal to synthetic oil demonstration plant in Erdos, Inner Mongolia.

Guidelines for safe and effective CCS in China

Tsinghua University together with the World Resources Institute have prepared a draft set of 'Guidelines for Safe and Effective CCS in China'. This effort is being funded with support from the US Department of State under the Asia Pacific Partnership (APP, 2009).

Regional opportunities for carbon dioxide capture and storage in China

In 2005, some initial collaborative work examined the possibilities for storing CO_2 emissions arising from the six coal-to-ammonia plants that had been established in China at that time (Meng and others, 2005). The emissions of concentrated streams of CO_2 from these plants ranged from some 0.6 Mt to 1.1 Mt. These CO_2 sources were mapped in relation to China's petroliferous sedimentary basins where prospective CO_2 storage reservoirs might be. Four promising pairs of CO_2 sources and sinks were identified.

In 2007, this idea was explored further by a consortium that included the Battelle Pacific Northwest National Laboratory; Chinese Academy of Sciences; Institute of Rock and Soil Mechanics; Leonardo Technologies Inc; Montana State University; Tsinghua University; and the USA/China Energy and Environmental Technology Centre (Dahowski and others, 2009). As has been reported in Chapter 8, the number of coal gasification sites has begun to increase very significantly and, although a significant proportion of the prospects will not proceed to commercial deployment, the opportunities for CO_2 capture have increased. Consequently, this second study included an indicative identification of CO_2 storage possibilities for all coal-to-chemicals plants that either were operational, under construction or had been announced as possible projects (Zheng and others, 2010). As such, it represented a snapshot of what the situation might be at some point in the future and provided an interesting extension of the earlier work.

The assessment suggested that, in due course, there might be some 400 coal gasification based industrial sites, producing ammonia or methanol as the primary product. These could represent sources for high-purity CO_2 streams of up to 208 Mt/y (NRDC, 2009). It was found that there might be 27 that would each emit more than 1 MtCO_2/y and potential CO_2 storage sites were sought close to these locations, on the basis of a literature review (Li, 2010). Of these, 18 sites were found to be within 10 km of prospective deep saline aquifer CO_2 storage sites and a further eight were within 100 km. The indicative compression, transport and storage costs in 2007 values on an 'nth' plant basis were thought to be under 21 US$/t of CO_2, which are lower than likely CCS costs for a large coal-fired power plant. As such, there might be promising opportunities for some lower cost demonstrations of CCS.

China's preference would most likely be for EOR applications rather than storage in an aquifer. However, on the basis of more comprehensive CO_2 storage capacity assessments (NZEC, 2009a; CAGS, 2011), it is not at all clear that this technique will be economically viable in many locations within China due to the heterogeneity of the oilfields. Nevertheless, this work represents a valuable first order assessment of the potential for deployment of CCS technologies in China and there is scope to undertake more focused, detailed assessments of the most promising options both in terms of capture potential and, especially, viable storage capacity.

9.3 Co-operation with international financial institutions

The major lending organisations are starting to support capacity-building projects as well as provide funding for major coal-related CCS projects.

9.3.1 Asian Development Bank

Once CCS projects extend towards commercial-scale operation, they would become the responsibility of the NDRC who would have to ensure that appropriate policy and regulations are in place. Currently, there are no policies or regulations that specifically address the capture and storage of CO_2, reflecting the view of the NDRC that the technology is at present too costly and unproven for Chinese application. However, if the initial phases of the GreenGen IGCC Initiative prove successful, the intended final phase is to build and operate a 400 MWe unit with pre-combustion CO_2 capture and probably the use of the CO_2 for EOR applications. This power plant would operate within the grid system and so regulations and standards would be required. With this in mind, the Asian Development Bank funded a capacity-building project to support the Chinese GreenGen IGCC-CCS Initiative (ADB, 2009).

The aims included identifying critical gaps, barriers, and associated risks in legal and regulatory aspects of CCS. The study noted that several regulatory frameworks on CCS have been or are in the process of being developed worldwide. These frameworks mainly focus on regulating CO_2 storage. All emerging regulations are similar in that they focus on issues related to exploration and storage permits, site characterisation, 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 (Yan, 2011).

Thus 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, which is not the case in China at present. Consequently, a new set of policy options would be needed at the national level to address technical, institutional, legal, regulatory and financial gaps, promote demonstration projects with a standardised approach that provides replicable cases for future projects.

The other point that has been highlighted is that technology demonstrations are undertaken to reduce technical and economic uncertainties such that commercial deployment can subsequently be undertaken. As such, 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.

The study also examined 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 study recommended that 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 that 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 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 NDRC. The NEA might be responsible for issuing exploration and storage permits while the Ministry of Environmental Protection might be responsible for EIA and monitoring issues.

9.3.2 World Bank

The World Bank has initiated three projects in China (Hart and Liu, 2010). It is establishing some CCS activities in partnership with CPIC, which has announced plans to establish IGCC projects within China although at this time those plans have not reached the stage of seeking approval from the NDRC. The Bank could potentially support the construction of such plants in order that a demonstration of a commercial prototype CCS project could be included (Kulichenko-Lotz, 2010). At present, it is funding studies for:

- optimisation and integration of CO_2 capture systems into an IGCC power plant;
- assessment of the different CO_2 transportation options;
- assessment of the technical feasibility and economics of CO_2 storage options;
- analysis of the market for CO_2 utilisation in different industries;
- assessment of the technical capacities of domestic equipment manufacturers;
- recommendations on technology transfer arrangements and IPR issues.

It is also seeking to strengthen the technical capacity of the NEA and the NDRC for the assessment of IGCC, CCS and carbon capture and utilisation proposals. Finally, it is supporting Tsinghua University, through a grant to the NDRC, to develop a methodology to credit emissions reductions from IGCC polygeneration plants under the Clean Development Mechanism.

9.4 Industrial enterprises co-operation

Ultimately there is a need to establish joint activities that progress beyond the MoU stage to the practical development of a specific project, which is expected to lead to demonstration and/or commercial ventures. A current example is the agreement between Peabody Energy, China Huaneng Group, and the Calera Corporation to pursue the development of a green coal energy campus in Inner Mongolia (PowergenWorldwide, 2011b). This project would include a new 1200 MWe supercritical power plant that would capture a portion of the CO_2 and convert it into green building materials. The plant would be fuelled with coal from a 12 Mt/y surface mine operated by Peabody while Huaneng would be the power plant operator. Calera would provide the technology to convert CO_2 into solid carbonates that can be used as building materials. Development of the project still requires permitting and regulatory approval.

A further example is the announcement, in October 2010, that Air Products has agreed with the Shanxi International Energy Group Co Ltd (SIEG) to perform a feasibility study and reference plant design on its proprietary oxyfuel CO_2 purification technology for potential installation at SIEG’s 350 MW Oxyfuel Electrical Generation Demonstration Project (Air Products, 2010). The demonstration project, should it ultimately be approved, would be located at SIEG’s power plant in Taiyuan, Shanxi Province.

More recently, Alstom Power and the China Datang Group agreed to develop two CCS trial projects. The intention is for Alstom to supply its capture technology for installation on the Daqing and Dongying coal-fired power plants in Heilongjiang Province and Shandong Province respectively, with some 1 Mt of CO_2 being used from each site for EOR in nearby oilfields (Bloomberg News, 2011).

10 The way forward

The key Government decision makers in the NDRC and NEA are currently not convinced that CCS is appropriate for China because of the high operational energy penalty and the capital/operational cost implications. In contrast, MOST and the state-owned Energy Enterprises are interested in the technology from R&D and commercial perspectives, and see a potentially significant benefit for China of positioning itself at the forefront of the technology development curve. However, they are not working within a domestic policy framework that will enable them to build on their impressive R&D progress to deliver full chain CCS technologies, at least in the near term.

The various international co-operative activities have increased Chinese capacity and raised awareness of CCS among many stakeholders concerning the viability of the technology and it seems essential that further such engagement will be needed, not just to take forward the development work but also to establish demonstration, and ultimately deployment, in China.

10.1 Policies and targets

Climate change and the need for mitigating actions have been increasingly highlighted within State Government directives, as seen with the implementation of the eleventh Five-Year Plan and especially with the early announcements of the twelfth Five-Year Plan. The vision for 2020 of reducing carbon intensity by 40–45% from 2005 levels, and meeting 15% of its total energy demand with non-fossil fuel, is a significant change from earlier policies of continuing rapid and significant growth in economic development with a corresponding increase in fossil energy demand. However, at the same time, rising per capita income and the continued economic importance of trade will drive demand for transport activity and fuel use, together with an ever greater absolute demand for electricity (Fridley and others, 2010). With regard to the latter point, the importance of the coal dominated power sector, which will continue to show significant growth over the next decade, must be emphasised.

The various modelling studies that have been undertaken by Chinese and international organisations, to develop possible energy growth scenarios for China, including the impact of various policy measures, are assisting the Government to make more informed decisions on the timing of possible large-scale deployment of CO_2 mitigation measures. This includes the prospects for CCS in the power and other coal intensive industrial sectors, and in relation to alternative approaches for low carbon energy provision and the wider societal costs of addressing climate change and its impacts (UNDP, 2010). All of these studies indicate that, under the current policies, while levels per unit of GDP should fall, absolute energy demand and CO_2 emissions will continue to rise, but at decreasing rates. It seems possible that, with the continued application of current policies and meeting announced targets and goals for energy efficiency improvements together with the further introduction of low and zero carbon technologies, a very broad plateau in annual CO_2 emissions may be reached by about 2030. If it is assumed that there will not be any premature retirement of advanced coal fired plant with replacement by, say, nuclear units, then it would almost certainly require the introduction of CCS to ensure that this expected plateau would decline in the period to 2050. Consequently, dialogue and co-operation with the China through various bilateral and multinational arrangements should be enhanced to determine how best to introduce CCS into the industrial coal utilisation sector.

10.2 CCS development

While none of the new coal power plants will include CCS within the period of the twelfth Five-Year Plan, it is a R&D priority for MOST, covering all capture options, transport and storage, with a near term emphasis on CO_2-driven EOR to help limit China's growing oil imports. The drivers are to reduce the energy penalties and high costs for the first generation technologies while implementing very significant levels of research at universities and institutes towards the development of second generation systems. Many of these R&D activities include a strong level of international co-operation, through capacity-building programmes with, amongst others, Australia, Canada, the European Commission, Italy, Japan, the UK and the USA. This reflects the critical need to engage China fully in all carbon mitigation opportunities and such activities have allowed all parties to improve their understanding of CCS issues in relation to China. This has provided a good basis for Chinese stakeholders to develop future plans for gaining practical experience with CCS technology, and should be continued.

With regard to progression beyond research, it is very significant that various power generation, coal and oil companies, such as Huaneng, Shenhua and PetroChina, are becoming involved in major CCS projects, including funding and implementing large industrial pilot-scale trials. Such activities build on the laboratory work, provide information for design of plant, allow an understanding of how capture systems work with real flue gas streams, and provide hands-on experience for some aspects of CO_2 utilisation and storage. Further large-scale activities are planned, which is a very important step towards demonstration of commercial prototypes.

10.3 CCS demonstration opportunities

It would be valuable for China to host certain CCS demonstration projects, both as showcases for its technology developments and also as a key step on the pathway towards commercial deployment. Thus, construction of a large-scale unit to demonstrate the technology would enable potential users to gain experience with all aspects of the process including construction, commissioning and operation. The goals of any CCS demonstration activities (NZEC, 2009b) would be to:

- establish the technology, including process integration and optimisation, at a scale that is large enough to allow subsequent plants to be built with confidence at commercial scale;
- prove that CCS works and is safe, thereby building public confidence;
- accelerate technology development in order to gain experience that will lead to subsequent cost reduction on larger scale plant.

The rationale and choices for demonstration projects in China are strategic considerations. The national context, technology status and other factors, such as feasibility, stakeholder interest, timing and cost, will be taken into account by the Chinese authorities in determining what is required. From a technical perspective, China is well positioned to move forward from the industrial pilot-scale trials towards demonstrations of various CO_2 capture and utilisation/storage options. These might include:

- a 1 Mt/y CO_2 capture project to be led by the Huaneng Group, which would build on their impressive 120 kt/y CO_2 capture and utilisation project on an advanced coal power plant near Shanghai. This would further provide an excellent opportunity for the CO_2 to be used in a major EOR project in a nearby oilfield;
- providing Phases 1 and 2 of the GreenGen project proceed successfully, including the 40–60 kt/y CO_2 EOR trial, there would be enormous merit in proceeding to Phase 3, which would include the construction of a 400 MWe IGCC with full CO_2 capture and the CO_2 to be used for an EOR demonstration in a nearby oilfield;
- a 1–3 Mt/y CO_2 capture and storage project to be led by Shenhua Group, which would scale up the current 100 ktCO_2/y integrated capture and storage in an aquifer project on the major coal to liquids demonstration plant near Ordos, Inner Mongolia.
- a 1 Mt/y CO_2 EOR trial in the Jilin Oilfield to be led by PetroChina and building on their smaller-scale activities.

In addition, it is important to recognise that the non-power gasification based coal to oil, gas and chemicals sector offers some potentially interesting CCS demonstration opportunities, even though it is much smaller in total coal use compared to the power sector. Many of the coal gasification sites are significant large-scale emitters of concentrated streams of CO_2. More importantly, there are clusters of sites in various industrial locations within China. These represent cumulative large point sources for CO_2 release and offer the prospect for demonstrations of integrated CCS networks within China at significantly lower marginal costs compared to the power sector and to individual non-power options. As such, they represent important early opportunities for demonstration that will aid China in building up expertise on all aspects of the CCS chain.

10.4 Financing such opportunities

The Chinese Government has indicated the state-owned enterprises would not undertake such demonstrations of commercial prototype CCS systems without significant financial support. Consequently there is a need for the global CCS community to fully engage with China as to how these projects can be best financed and how (and to what level) the information arising can be disseminated to aid complementary projects elsewhere. The official recognition at the UNFCCC meeting in Mexico in December 2011 that CCS has a critical role to play, as part of a portfolio of actions in reducing global CO_2 emissions, may provide a support mechanism that will clear the way for developing countries to finance CCS projects. Recently, the ADB has proposed the creation of a CCS dedicated multilateral funding mechanism to provide capital cost subsidies and incentives for CCS demonstration in developing countries for the period at least up to 2020 (ADB, 2011).

At the same time, there is a need to ascertain what might comprise a demonstration project. It is important to recognise that for China, CO_2 utilisation through CO_2 EOR is a major interest. This technique should be eligible for inclusion in a CCS project provided that the CO_2 injection and storage is monitored to determine the level of permanent CO_2 storage. That said, it seems unlikely that ultimately EOR will be able to utilise a significant proportion of China's likely CO_2 emissions, due to the nature of the oilfields. Consequently, storage in saline aquifers would need to be encouraged as a priority since it would improve the understanding of what are potentially the largest storage formations and for which there is a relative lack of knowledge.

These possible CCS demonstration projects would operate in conjunction with either new or existing power plants and industrial facilities. The expectation is that external funding would be needed to support the incremental costs incurred as a result of the CCS activities.

10.5 Further co-operation prospects

While the R&D on the technical development aspects of CCS, including international co-operation, is progressing well, China might benefit from including participation in broader knowledge-sharing agreements.

While the potential to use captured CO_2 to enhance oil production is of great interest, initial collaborative storage capacity assessments showed that, at least in North-East China, the oilfields where CO_2 might be used for EOR are mostly of small capacity relative to the CO_2 emissions of a large coal-fired power plant (NZEC, 2009). Further capacity-building work is under way (CAGS, 2011) to complement the earlier work. China is starting to build on these activities to undertake a comprehensive national survey, covering oil and gas reservoirs in all regions of China, as well as a rigorous assessment of saline aquifer storage capacities. Such work should include:

- national and regional storage mapping, for example a CO_2 storage atlas for China, including defining site-selection criteria and site-characterisation methodologies;
- detailed scientific, technological and engineering assessments of CO_2 EOR opportunities;
- depleted oilfield and gasfield storage assessment, which could cover capacity and availability, as well as facilities, integrity and re-use;
- aquifer storage mapping, assessment of capacity and integrity, and site characterisation.

It is also important to use the information arising from this survey to establish criteria for siting new coal power plants and other industrial facilities in order to take into account possible CO_2 storage locations as well as access to coal, water, the grid and other facilities. There is scope for co-operation on such activities.

A related issue is the need to ensure that storage of CO_2 will be safe on a long-term basis, because of the potential risks to people and the environment associated with release of CO_2. In order to address this, China needs to gain experience with monitoring and verification as part of an overall risk assessment process.

In China, there is to date limited progress in developing legal and regulatory frameworks for the introduction of CCS. Such regulations will be needed to support the demonstration and deployment of CCS in China, particularly for the storage of CO_2 underground but also to address the safety of pipelines carrying supercritical CO_2 and the environmental impact of CCS plants. There are also issues such as long-term liability and financial responsibility post-closure that need to be addressed. There are international initiatives to frame such regulations and China has an opportunity to participate and draw lessons from the experiences of other countries in deciding how it wants to proceed on these critical issues (NZEC, 2009a).

10.6 National resource implications

It is important to recognise that if coal-fired power plants are fitted with CCS then more coal has to be burned. This is a result of the efficiency losses associated with the CO_2 capture technology. Consequently, if significant deployment of CCS should be required, this would have a very adverse impact on China's coal supply transportation systems. At the same time, such coal-fired plants would require equally significant increases in water usage, which may not be readily available as the new plants would most likely be built at the coal-power bases, which will mostly be in arid regions of the country (IEAGHG, 2011; Chinadialogue, 2011b). As such, these additional environmental consequences cannot be ignored when weighing up the needs and benefits of CCS introduction to China. Support for studies to assess these issues should be encouraged.

10.7 Commercial considerations

China is becoming well positioned to move to the forefront on many aspects of CCS, certainly on CO_2 capture and, for the moment, on CO_2 utilisation. In terms of domestic deployment, the various modelling scenarios suggest that China is unlikely to move to introduce the technology before 2025-30, at best, although that may well change should a robust link with CDM and other financing mechanisms become established.

China is becoming well-placed to become a serious supplier of CO_2 capture technology alongside its initiatives to export advanced supercritical coal fired boilers within the Asian region and elsewhere, where it has a significant cost advantage compared to OECD suppliers. It would also be well-placed for the various gasification subsectors, including IGCC should its ongoing development programme prove successful. The three major Chinese heavy engineering equipment manufacturers, in Shanghai, Harbin and Dongfang, are world leaders in the production of advanced coal-fired power plant and large gasification facilities, with production facilities to international standards. They and the leading industrial enterprises are well-placed to diversify their product range to include CO_2 capture and related systems.

11 References

973.com (2011) *The fundamental research of large-scale and high-efficiency entrained flow coal gasification process*. Available from: http://www.973.gov.cn/English/ReadItem.aspx?itemid=504, National basic research programme of China (2011)
Adams M, Bonnell L (2009) *Purification of CO_2 for sequestration and low emissions venting*. Presented at Gasification Technologies Conference, USA (6 October 2009)
ADB (2009) *People's Republic of China: carbon dioxide capture and storage demonstration, strategic analysis and capacity strengthening*. Asian Development Bank TA 7286- PRC (August 2009)
ADB (2011) *Carbon dioxide capture and storage in developing countries: analysis of key policy issues and barriers*. Asian Development Bank TA 7278-REG: Final Report (April 2011)
Aden N, Fridley D, Zheng N (2009) *China's coal: demand, constraints, and externalities*. Available from: http://escholarship.org/uc/item/8kk9n3rr, Lawrence Berkeley National Laboratory, USA (July 2009)
AirProducts (2010) *Air Products to work with China's SIEG on 350 MW Oxyfuel Electrical Generation Demonstration Project*. Available from: http://www.airproducts.com/PressRoom/CompanyNews/Archived/2010/04Oct2010b.htm (4 October 2010)
APCO (2010) *China's 12th Five-Year Plan*. Available from: http://www.apcoworldwide.com/content/PDFs/Chinas_12th_Five-Year_Plan.pdf, (10 December 2010)
APP (2010) *China-USA: Guidelines for safe and effective CCS in China*. Available from: www.asiapacificpartnership, Tsinghua University and World Resources Institute. (2010)
Belfer Centre (2010) *Advancing carbon capture and sequestration in China: A global learning laboratory*. Available from: http://belfercenter.ksg.harvard.edu/publication/20681/advancing_carbon_capture_and_sequestration_in_china.html, China Environment Series, Issue 11 (*2010/2011*)
Benelli (2010) *Early opportunities for CCS in China*. Available from: http://www.iea.org/work/2010/most/benelli.pdf, ENEL Engineering & Innovation Division. Presented at the IEA-MOST Workshop on Fossil Fuel Technologies, Beijing, China (10-11 June 2010)
Bloomberg News (2010) *Chinese CDM fund to have $1.5 billion for clean-energy projects by 2012*. Available from: http://www.bloomberg.com/news/2010-10-22/china-cdm-fund-to-have-1-5-billion-for-clean-energy-projects-by-2012.html, (22 October 2010)
Bloomberg News (2011) *Alstom, Datang to Build Trial Carbon-Capture Projects in China*. Available from: http://www.bloomberg.com/news/2011-09-21/alstom-datang-to-build-trial-carbon- capture-projects-in-china.html, (September 2011)
Bo P (2010) *CO_2 storage and enhanced oil recovery in Jilin Oil Field*. Available from: http://www.ga.gov.au/image_cache/GA16242.pdf, University of Petroleum, Beijing, China (21 January 2010)
Bo P (2011) University of Petroleum, Beijing, China, *personal communication* (May 2011)
BP (2003) *BP-Tsinghua University Clean Energy Research and Education Centre*. Available from: http://www.bp.com/sectiongenericarticle.do?categoryId=9011369&contentId=7025853 (2003)
BP (2008) *BP and CAS sign up to clean energy commercialisation centre*. Available from: http://www.bp.com/genericarticle.do?categoryId=7106&contentId=7049660 (26 November 2008)
Business China (2010) *China to issue 12th Five-Year Plan for power industry in Dec – Official*. Available from: http://en.21cbh.com/HTML/2010-12-1/China-Electricity.html (1 December 2010)
Cachet (2009) *Carbon dioxide capture and hydrogen production from gaseous fuels*. Available from: http://www.cachetco2.eu/ (2009)
CAGS (2011) *The China Australia geological storage of CO_2 project*. Available from: http://www.cagsinfo.net/ (2011)
Cai N (2010) *Development of coal gasification & polygeneration in China*. Available from:

http://www.iea.org/work/2010/most/cai.pdf, Presented at the IEA-MOST Workshop on Fossil Fuel Technologies, Beijing, China (11 June 2010)
Cao J (2009) GreenGenCo, Beijing, China, *personal communication* (October 2009)
Cao J (2011) GreenGenCo, Beijing, China, *personal communication* (May 2011)
Caprice (2009) *The Caprice project.* Available from: www.caprice-project.eu (2009)
Capture Ready (2010a) *China Shenhua CCS demonstration project in Erdos casts a vague prospect*. Available from: http://www.captureready.com/forum/showthread.php?tid=141 (20 July 2010)
Capture Ready (2010b) *Australia, China to cooperate on carbon capture feasibility study*. Available from: http://www.captureready.com/EN/Channels/News/showDetail.asp?objID=2082 (17 December 2010)
Capture Ready (2011a) *Erdos CCS project successfully operated*. Available from: http://www.captureready.com/EN/Channels/News/showDetail.asp?objID=2185&isNew (21 February 2011)
Capture Ready (2011b) *Optical Valley selected as the Joint Research Centre of China- America clean energy*. Available from: http://www.captureready.com/EN/Channels/News/showDetail.asp?objID=2198&isNew (1 March 2011)
Carbon Capture Journal (2010a) *Study launched to find CO_2 purity requirements for CCS Projects/Policy*. Available from: http://www.carboncapturejournal.com/displaynews.php?NewsID=569 (11 May 2010)
Carbon Capture Journal (2010b) *UN accepts CCS in the Clean Development Mechanism projects / policy*. Available from: http://www.carboncapturejournal.com/displaynews.php?NewsID=703 (13 December 2010)
Carbon Capture Journal (2011a) *Making the case for CCS in the CDM*. Available from: http://www.carboncapturejournal.com/displaynews.php?NewsID=713 (10 January 2011)
Carbon Capture Journal (2011b) *China's growing CCS activities in action*. Available from: http://www.carboncapturejournal.com/displaynews.php?NewsID=712 (10 January 2011)
Carter L (2011) *Enhanced oil recovery & CCS*. Available from: http://www.uscsc.org/Files/Admin/Educational_Papers/Enhanced%20Oil%20Recovery%20and%20CCS-Jan%202011.pdf, United States Carbon Sequestration Council (14 January 2011)
CAS (2008) CAS, BP ink agreement on commercialisation of clean energy. Available from: www.english.cas.ac.cn/english/news/detailnewsb.asp?InfoNo. Chinese Academy of Sciences (22%January 2008)
Chinacsr (2009) *Shanghai lands world's largest carbon capture project*. Available from: http://www.chinacsr.com/en/2009/08/06/5850-shanghai-lands-worlds-largest-carbon-capture-project/ (6 August 2009)
Chinacsr (2010) *China develops its first CO_2 capture and storage project*. Available from: http://www.chinacsr.com/en/2010/06/16/7709-china-develops-it-first-co2-capture-and-storage-project/ (16 June 2010)
Chinadialogue (2011a) *Behind China's green goals*. Available from: http://www.chinadialogue.net/article/show/single/en/4181-Behind-China-s-green-goals (24 March 2011)
Chinadialogue (2011b) *Pipeline pressures in North China*. Available from: http://www.chinadialogue.net/article/show/single/en/4332-Pipeline-pressures-in-north-China?utm_source=Chinadialogue+Update&utm_campaign=5b28269ea3-newsletter+03+May+2011&utm_medium=email (3 June 2011)
China Daily (2009) *Emissions to peak at 2030: report*. Available from: http://www.chinadaily.com.cn/bizchina/2009-08/18/content_8581365.htm (18 August 2009)
China Daily (2010) *Carbon tax likely, expert forecasts*. Available from: http://www.chinadaily.com.cn/china/2010-05/10/content_9826546.htm (10 May 2010)
China Daily (2011a) *Key targets of China's 12th five-year plan*. Available from: http://www.chinadaily.com.cn/china/2011npc/2011-03/05/content_12120283.htm (5 March 2011)
China Daily (2011b) *Road map for social, economic development unfolded*. Available from: http://www.chinadaily.com.cn/china/2011npc/2011-03/06/content_12122579.htm (6 March 2011)
China FAQs (2011) *Cleaning China's Air: First Regional Air Quality Regulations*. Available from:

http://www.chinafaqs.org/blog-posts/cleaning-chinas-air-first-regional-air-quality-regulations (2 June 2010)
China.org (2011) *Senior official calls for cap on coal consumption*. Available from: http://www.china.org.cn/china/NPC_CPPCC_2011/2011-03/13/content_22122403.htm (13 March 2011)
Climate Policy Initiative (2010) Review of low-carbon development in China's key sectors. Available from: www.climatepolicyinitiative.org/generic_datas/view/publication/2, Beijing (November 2010)
COACH (2009) Cooperation action within CCS China-EU. Available from: http://www.co2-coach.com/ (2009)
Coleman P (2011) Canberra, Australia, Department of Resources, Energy and Tourism, Government of Australia, *personal communication* (August 2011)
CO_2Sense Yorkshire (2010) *CO_2 network to the future*. Available from: http://www.co2sense.org.uk/uploads/public/CCS%20Brochure.pdf (2010)
CSLF (2009) Carbon sequestration leadership forum. Available from: http://www.cslforum.org/publications/documents/Washington2008/DahowskiROCCSProjectUpdate111608.pdf (2009)
CSLF (2011) *A global response to the challenge of climate change*. Available from: http://www.cslforum.org/ (2011)
Dahowski R, Li X, Davidson C, Wei N, Dooley J (2009) *Regional opportunities for carbon dioxide capture and storage in China: A Comprehensive CO_2 storage cost curve and analysis of the potential for large scale carbon dioxide capture and storage in the People's Republic of China*. Available from: http://www.cslforum.org/projects/china_regional.html (2009),
Davidson R (2009) *Post-combustion carbon capture – solid sorbents and membranes*. CCC/144, London, UK, IEA Clean Coal Centre, 64 pp (Jan 2009)
Davidson R, Santos S (2010) *Oxyfuel combustion of pulverised coal*. CCC/168, London, UK, IEA Clean Coal Centre, 63 pp (Jun 2010)
DECC (2011) *Chinese advanced power plant carbon capture options*. Available from: http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/carbon%20capture%20and%20storage/1_20100217160042_e_@@_chineseadvancedpowerplantcc.pdf (2011)
Dong C (2011) North China Electric Power University, Beijing, China, *personal communication* (May 2011)
E&P (2011) *Shell and Wison to develop new generation clean gasification technology*. Available from: http://www.epmag.com/Production/ProductionNews/2011/February/item77363.php (15 February 2011)
EIA (2010a) *International Energy Outlook 2010*. Available from: http://www.eia.doe.gov/oiaf/ieo/ US Energy Information Administration. Report DOE/EIA-0484(2010) (27 July 2010)
EIA (2010b) *International Energy Outlook 2010: Energy related carbon dioxide emissions.* Available from: http://www.eia.doe.gov/oiaf/ieo/emissions.html, US Energy Information Administration. Report DOE/EIA-0484 (2010)
EPSRC (2010a) *Collaborative UK-China research projects in carbon capture and storage technologies*. Available from: http://www.epsrc.ac.uk/funding/calls/2010/Pages/carboncapture.aspx, Engineering and Physical Sciences Research Council UK (April 2010)
EPSRC (2010b) *UK- China research projects in carbon capture/storage*. Available from: http://gow.epsrc.ac.uk/ViewPanelROL.aspx?PanelId=5030&RankingListId=6929, Engineering and Physical Sciences Research Council UK (3 September 2010)
Europa (2005) *EU and China Partnership on Climate Change*. Available from: http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/05/298 (2 September 2005)
Europa (2009a) *Carbon Capture and Geological Storage (CCS) in emerging developing countries: financing the EU-China Near Zero Emissions Coal Plant project*. Available from: http://europa.eu/rapid/pressReleasesAction.do?reference=IP/09/1022 (25 June 2009)
Europa (2009b) *The EC-China MoU on Cooperation on NZEC through CCS signed*. Available from: http://eeas.europa.eu/delegations/china/press_corner/all_news/news/2009/20091201_02_en.htm (27 November 2009)
Fang M (2011) *Overview of CO_2 capture programme in Zhejiang University*. Available from:

http://www.carbontreasure.org/UploadFiles/20110401015408854.pdf. Presented at a seminar on progress in post-combustion CO_2 capture supported by the Australian Government through the Asia-Pacific Partnership on Clean Development and Climate, Beijing, China (19 April 2011)
Fernando R (2008) *Coal gasification.* CCC/140, London, UK, IEA Clean Coal Centre, 56 pp (Oct 2008)
Freund P (2009) Cheltenham, UK, *personal communication* (October 2009)
Fridley D, Zheng N, Aden N (2010) *What can China do? China's best alternative outcome for energy efficiency and CO_2 emissions*. Available from: http://escholarship.org/uc/item/2jj8f0kv;jsessionid=850030B6546FB92789F2F93ECF075B39, China Energy Group, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory (July 2010)
Gassnova (2010) *International CCS technology survey: Issue 6*. Available from: http://www.gassnova.no/frontend/files/CONTENT/CCSWorld/IN-report-issue6-2009.pdf (February 2010)
Gasworld (2010) *CO_2 capture facilities for Chinese coal-fired plants started operation*. Available from: http://www.gasworld.com/news.php?a=4537 (23 March 2010)
GCCSI (2011) *China's 12th Five Year Plan*. Available from: http://www.globalccsinstitute.com/community/blogs/authors/rposner/2011/03/24/china%E2%80%99s-12th-five-year-plan, Global CCS Institute, Australia (24 March 2011)
GE Energy (2009) *GE Energy Introduces its largest capacity quench gasifier, configured for large gasification projects*. Available from: http://www.gepower.com/about/press/en/2009_press/040109.htm (1 April 2009)
GEOCAPACITY(2009) *Assessing European capacity for geological storage of carbon dioxide.* Available from: http://www.geology.cz/geocapacity (2009)
Global Times (2010) *China looks to promote strategic emerging industries*. Available from: http://china.globaltimes.cn/chinanews/2010-09/571488.html (9 September 2010)
GreenGen (2008) *The GreenGen project*. Available from: http://greengen.com.cn/en/index.asp (2008)
Hart C, Liu H (2010) *Advancing carbon capture and sequestration in China: a global learning laboratory*. Available from: http://www.wilsoncenter.org/topics/pubs/CES%2011%20pp.%2099-130.pdf (2010)
Hegan L (2011) *CO_2 transportation - networking pays off*. Available from: http://www.globalccsinstitute.com/community/blogs/authors/larryhegan/2011/05/23/co2-transportation-networking-pays. Global CCS Institute (23 May 2011)
Henderson C (2010) *Chemical looping combustion of coal*. CCC/178, London, UK, IEA Clean Coal Centre, 49 pp (Dec 2010)
Higman C, Van der Burgt M (2003) *Gasification*. New York, Gulf Professional Science - Elsevier Science USA, 391 pp (2003)
IEA (2009a) *World energy outlook 2009*. Available from: http://www.worldenergyoutlook.org/docs/weo2009/WEO2009_es_english.pdf, International Energy Agency, Paris, France (November 2009)
IEA (2009b) *Technology roadmap: carbon capture and storage*. Available from: www.iea.org/papers/2009/CCS_Roadmap.pdf, International Energy Agency, Paris, France (2009)
IEA (2010a) *Energy technology perspectives 2010: Executive summary*. Available from: http://www.iea.org/techno/etp/etp10/English.pdf, International Energy Agency, Paris, France (1 July 2010)
IEA (2010b) *CO_2 emissions from fuel combustion*. Available from: http://www.iea.org/co2highlights/co2highlights.pdf, International Energy Agency, Paris, France (2010)
IEAGHG (2011) *Water usage and loss analysis of bituminous coal fired power plants with CO_2 capture*. Report 2010/05 IEA Greenhouse Gas Programme (March 2011)
Inouye J, Kim A, Wang W, Zabata A (2008) *Coal to methanol conversion*. Available from www.docstoc.com/docs/20862732/Coal-to-Methanol-Conversion, University of California (22 May 2008)
Kulichenko-Lotz N (2010) *Update on World Bank CCS work programme*. Available from:

http://www.cslforum.org/publications/documents/Warsaw2010/Kulichenko-PG-WorldBankPresentation-Warsaw1010.pdf, World Bank (7 October 2010)
Kunze C, Spliethoff H (2011) Evaluation of an IGCC concept with post combustion CO_2 capture. Presented at: *5th International Conference on Clean Coal Technologies 2011,* Zaragoza, Spain (8-12 May 2011)
Kuuskraa V (2004) *Estimating CO_2 storage capacity in saline aquifers*. Available from: http://www.netl.doe.gov/publications/proceedings/04/carbon-seq/077.pdf, Presented at the 3rd annual conference on carbon capture and sequestration. Alexandria, Virginia, USA (3-6 May 2004)
Lawrence Berkeley National Laboratory (2011) *China's energy and carbon emissions: outlook to 2050*. Available from: http://china.lbl.gov/publications/2050-outlook, US Department of Energy Contract No. DE-AC02-05CH11231. Report LBNL-4472E (April 2011)
Li E (2011) British Embassy, Beijing, China, *personal communication* (March 2011)
Li X (2010) *CCS potential contribution and early opportunities in China*. Available from: www.cagsinfo.net/pdfs/workshop2/CAGS-Workshop-Two-Program.pdf, Presented at the CAGS workshop on aquifer storage of CO_2, Wuhan, Hubei Province, China (26-29 October 2010)
Liu H; NI W, Li Z, Ma L (2008) Strategic thinking on IGCC development in China*. Energy Policy* 36 (1), pp 1-11 (2008)
Liu L (2008) Huaneng Thermal Power Research Institute, Xian, China, *personal communication* (July 2008)
Liu L (2011) Huaneng Clean Energy Research Institute, Beijing, China, *personal communication* (May 2011)
Mao J (2011) Tsinghua University, Beijing, China, *personal communication* (May 2011)
Meng K, Celia M, Williams R (2005) *Opportunities for low-cost carbon capture and storage demonstration projects in China*. Available from: http://www.netl.doe.gov/publications/proceedings/05/carbon-seq/Poster%20226.pdf, Presented at the Fourth Annual Conference on Carbon Capture and Sequestration, Alexandria, Virginia (2-5 May 2005)
MEP (2009) Ministry of Environmental Protection of the People's Republic of China. Available from: http://english.mep.gov.cn/ (2009)
Metering China (2010) *State Grid's investment in 12th FYP to exceed 0.17 trillion yuan*. Available from: http://www.meteringchina.com/en/html/Industry-News/12-153.html (12 November 2010)
Minchener A (2010) *Developments in China's coal-fired power sector*. CCC/163, London, UK, IEA Clean Coal Centre, 55 pp (Jan 2010)
Minchener A (2011) *Coal-to-oil, gas and chemicals in China.* CCC/181, London, UK, IEA Clean Coal Centre, 49 pp (Feb 2011)
MOST (2007a) *China's scientific and technological actions on climate change: introductive information*. Available from: http://www.most.gov.cn/eng/pressroom/200706/t20070615_50483.htm, Ministry of Science and Technology of the People's Republic of China. (14 June 2007)
MOST (2007b) *Key technologies R&D programme*. Available from: http://www.most.gov.cn/eng/programmes1/200610/t20061009_36224.htm, Ministry of Science and Technology of the People's Republic of China. (2007)
MOST (2010) *Carbon capture, utilisation and strorage development in China*. Available from: http://no.china-embassy.org/eng/kj/achivements/P020101014674327840098.pdf, Edited by the Department of Social Development and the Administrative Centre for China's Agenda 21, of the Ministry of Science and Technology of China (2010)
MOST (2011a) Ministry of Science and Technology of the People's Republic of China. Available from: www.most.gov.cn/eng/ (2011)
MOST (2011b) *Carbon capture, utilisation and storage: technology development in C*hina. Available from: http://www.acca21.org.cn/gest/etc/CCUS_en.pdf (September 2011)
Movecbm (2009) *Monitoring and evaluation of coal bed methane*. Available from: http://www.movecbm.eu/ (2009)
Muztagh (2011) Map of China. Available from: http://www.muztagh.com/map-of-china/ (2011)
Nature (2011) *Low-cost carbon-capture project sparks interest*. Available from: http://www.nature.com/news/2011/110118/full/469276a.html (18 January 2011)
NDRC (2006) *Medium and long term energy conservation plan*. Available from: http://www.gov.cn.

National Development and Reform Commission (6 March 2006)
NDRC (2007a) *Proposal to State Council for accelerating decommission of inefficient small size generating units.* National Development and Reform Commission (2007)
NDRC (2007b) *Regulation on energy conservation power generation dispatching (try out)*. Jointly issued by NDRC, SEPA, SERC and Office of National Leading Group on Energy. (2007)
NDRC (2007c) *China's national climate change programme*. Available from: http://www.china.org.cn/english/environment/213624.htm, National Development and Reform Commission (4 June 2007)
NDRC (2011a) Main Functions of the NDRC. Available from: http://en.ndrc.gov.cn/mfndrc/default.htm (2011)
NDRC (2011b) National Energy Administration. Available from: http://en.ndrc.gov.cn/mfod/t20081218_252224.htm (2011)
NETL (2010) *Gasification database*. Available from: http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html (2010)
NRDC (2009) *Identifying near-term opportunities for carbon capture and sequestration (CCS) in China*. Available from: http://www.nrdc.org/international/chinaccs/files/fchinaccs.pdf (October 2009)
NZEC (2009a) *China: UK cooperation-near zero emissions from coal fired power plants*. Available from http://www.nzec.info/en/ (2009)
NZEC (2009b) *Latest news: final China-UK NZEC summary report now publicly available.* Available from: http://www.nzec.info/en/ (October 2009)
Orr F, Taber J (1984) *Use of carbon dioxide in enhanced oil recovery*. Available from: www.sciencemag.org/content/224/4649/563.short, Science Vol. 224 no. 4649 pp. 563-569 (11 May 1984)
Palla R (2010) *CCS options & cost reductions with new UOP SELEXOLTM process flow schemes.* Presented at Gasification Technologies Conference, Washington DC, USA (31 Oct-3 Nov 2010)
Pennenergy (2011) *GE, Shenhua form cleaner coal JV to advance coal gasification technologies in China*. Available from: http://www.pennenergy.com/index/power/display/0555391234/articles/pennenergy/ power/coal/2011/ january/ge_-shenhua_form_cleaner.html (19 January 2011)
People's Daily Online (2010a) *China's National Energy Commission is established*. Available from: http://english.peopledaily.com.cn/90001/90778/90862/6880658.html (27 January 2010)
People's Daily Online (2010b) *China to cut fossil fuel in total energy mix to 85 pct by 2020: ex-lawmaker*. Available from: http://english.peopledaily.com.cn/90001/90778/90862/7139699.html, (14 September 2010)
People's Daily Online (2011) *The State Council*. Available from: http://english.peopledaily.com.cn/data/organs/statecouncil.shtml, (2011)
Platts (2011) *China meets 5-year energy conservation targets by end 2010:* NDRC Available from: http://www.platts.com/RSSFeedDetailedNews/RSSFeed/Coal/8385675 (7 January 2011)
Power (2010) *China's largest electric utility centralizes its clean energy programs*. Available from: http://www.powermag.com/press_releases/Chinas-Largest-Electric-Utility-Centralizes-Its-Clean-Energy-Programs_3321.html (14 December 2010)
PowergenWorldwide (2009) *US-China initiatives for renewable energy projects*. Available from: http://www.powergenworldwide.com/index/display/articledisplay/370966/articles/powergenworldwide/emissions-and-environment/energy-efficiencies/2009/11/us-china-initiatives-for-renewable- energy-projects.html (17 November 2009)
PowergenWorldwide (2010) *ADB approves $135m loan for IGCC power plant in China*. Available from: http://www.powergenworldwide.com/index/display/articledisplay/articles/powergenworldwide/coal-generation/coal-generation-equipment/2010/02/adb-approves___135m.html (10 February 2010)
PowergenWorldwide (2011a) *US-China sign clean coal technology work plan*. Available from: www.powergenworldwide.com/index/display/.../articles/.../bw-china.html (18 January 2011)
PowergenWorldwide (2011b) *Peabody Energy looking to develop 1200 MW coal plant in China.* Available from: http://www.powergenworldwide.com/index/display/articledisplay/6386027210/articles/powergenworldwide/coal-generation/new-projects/2011/01/Peabody-to-build-plant-China.html (20 January 2011)
Qian Z (2011) *CO_2 in the cement industry*. CCC/184, London, Uk, IEA Clean Coal Centre, 85 pp (Jun 2011)

Reuters (2008) *Japan, China to join in $300 mln CO_2 project: paper*. Available from: http://uk.reuters.com/ article/environmentNews/idUKT6916020080503?pageNum (3 May 2008)
Reuters (2009a) *China study urges greenhouse gas caps, peak in 2030*. Available from: http://in.reuters.com/article/2009/08/17/china-climate-idINSP43427720090817?pageNumber=1 (17 August 2009)
Reuters (2009b) *China climate change report sets out options*. Available from: http://www.reuters.com/article/2009/08/17/idUSPEK290155 (17 August 2009)
Reuters (2011) *China's CO_2 emissions rose 10 percent in 2010: BP data*. Available from: http://www.reuters.com/article/2011/06/08/us-energy-bp-emissions-idUSTRE75728120110608 (8 June 2011)
Rui H, Morse R, Gang H (2010) Remaking the world's largest coal market: the quest to develop large coal-power bases in China. Available from: http://pesd.stanford.edu/publications/remaking_the_worlds_largest_coal_market_the_quest_to_devel op_large_coalpower_bases_in_china/, Program on Energy and Sustainable Development, Stanford University (2010)
Rui X (2011) South East University, China, *personal communication* (May 2011)
Santos S (2011) *Challenges in dealing with the non-CO_2 components from different CO_2 capture technologies*. Available from: http://www.ieaghg.org/docs/General_Docs/IEAGHG_Presentations/S._Santos_IEAGHG_-__CO2_Pipeline_Forum.pdf, IEA Greenhouse Gas R&D Programme. Presented at the 2nd CO_2 Pipeline Forum, Newcastle, UK (22nd June 2011)
Seevam P and others (2008) *Transporting the next generation of CO_2 for carbon capture and storage: the impact of impurities on supercritical CO_2 pipelines*. Proceedings of IPC2008 7th International Pipeline Conference, IPC2008-64063 Calgary, Alberta, Canada (29 Sept-3 Oct 2008)
Stanford University (2011) *The global climate and energy project*. Available from: http://gcep.stanford.edu/, Stanford University, USA (2011)
State Grid Corporation of China (2010) *Emission reduction target for 11th Five-Year Plan accomplished ahead of schedule*. Available from: http://www.sgcc.com.cn/ywlm/mediacenter/industrynews/12/237549.shtml (15 December 2010)
STRACO2 (2009) *Support to regulatory activities for carbon capture and storage*. Available from: http://www.euchina-ccs.org/, (2009)
Su W (2009) GreenGen Co, Beijing, China, *personal communication* (October 2009)
Sxcoal (2010a) *China carbon emissions may reach peak by 2030*. Available from: http://en.sxcoal.com/NewsDetail.aspx?cateID=173&id=34767 (24 July 2010)
Sxcoal (2010b) *China to limit coal production to 3.6-3.8 Bt*. Available from: http://en.sxcoal.com/414/40020/DataShow.html, Sxcoal (2 November 2010)
The Climate Group (2011) *Delivering low carbon growth: Executive summary*. Available from: www.theclimategroup.org/.../delivering-low-carbon-growth-a-guide-to-chinas-12th-five-year-plan/, (7 March 2011)
The Green Leap Forward (2009) *China to adopt binding goal to reduce CO_2 emissions per unit GDP by 40 to 45% of 2005 levels by 2020*. Available from: http://greenleapforward.com/2009/11/26/china-to-adopt-binding-goal-to-reduce-co2-emissions-per-unit-gdp-by-40-to-45-of-2005-levels-by-2020 (November 2009)
The Hydrogen Journal (2011) *Shell to develop coal gasification technology in China*. Available from: http://www.h2journal.com/displaynews.php?NewsID=632 (18 February 2011)
UNDP (2010) *China and a sustainable future: towards a low carbon economy and society*. Available from: http://hdr.undp.org/en/reports/national/.../china/name,19646,en.html (April 2010)
Wall Street Journal (2011) *China's energy consumption rises*. Available from: http://online.wsj.com/article/SB10001424052748704615504576171922168262078.html (28 February 2011)
Wang S (2011a) *CO_2 capture in Tsinghua University*. Available from: http://www.carbontreasure.org/UploadFiles/20110401015408854.pdf, Presented at a seminar on progress in post-combustion CO_2 capture, supported by the Australian Government through the Asia-Pacific Partnership on Clean Development and Climate, Beijing, China (19 April 2011)
Wang S (2011b) Tsinghua University, Beijing, China, *personal communication* (May 2011)
Webb M (2008) Department of Energy & Climate Change, London, UK, *personal communication* (2008)

WRI (2011) *How does China's 12th Five-Year Plan address energy and the environment?* Available from: http://www.wri.org/stories/2011/03/how-does-chinas-12th-five-year-plan-address-energy-and-environment, World Resources Institute (7 March 2011
Xiao Y (2007) *IGCC and co-production in China*. Available from: http://belfercenter.ksg.harvard.edu/files/04-yunhan_xiao.pdf, Presented at the International Workshop on IGCC & Co-Production and CO2 Capture & Storage, Beijing, China (23 May 2007)
Xinhuanet (2010) *China's first carbon capture plant to start operation by year-end*. Available from: http://news.xinhuanet.com/english2010/business/2010-06/02/c_13329759.htm (2 June 2010)
Xu Z (2005) *Problems that need to be considered in developing gasification technology in China*. Coal Science Research Institute, Beijing Coal Chemical Research Centre, China (2005).
Yan J (2011) *Roadmap for the demonstration of carbon capture and storage in China.* Final report to the ADB on Project ADB TA 7286 (PRC) People's Republic of China Carbon Dioxide Capture and Storage Demonstration – Strategic Analysis and Capacity Strengthening (January 2011)
Yang S (2011) CPI Yuanda Environmental Protection Engineering Co, China, p*ersonal communication* (March 2011)
Zhang J (2010) *Overview of CCUS activities in China*. Available from: http://www.cagsinfo.net/pdfs/workshop2/Session-1/Overview-CCUS-Activities-China.pdf, Presented at the CAGS aquifer storage of CO_2 workshop, Wuhan, Hubei Province, China (26-29 October 2010)
Zhang J (2011) Tsinghua University, Beijing, China, *personal communication* (May 2011)
Zhang J, Liu B, Li Q, Zhang X (2011) *CO_2 capture from coal fired power plant and EOR in Shengli Oilfield of Sinopec China*. Available from: http://www.ieaghg.org/docs/General_Docs/PCCC1/Abstracts_Final/pccc1Abstract00039.pdf, Presented at the 1st Post Combustion Capture Conference of the IEA Greenhouse Gas Programme, Abu Dhabi, (17th-19th May 2011)
Zheng Z, Larson E, Li Z, Liu G, Williams R (2010) *Near-term mega-scale CO_2 capture and storage demonstration opportunities in China*. Available from: http://pubs.rsc.org/en/Content/ArticleLanding/2010/EE/B924243K, Energy Environ. Sci., 2010, 3, 1153–1169
Zhong P (2010) *China's policies and actions on carbon capture and storage*. Available from: http://www.ga.gov.au/image_cache/GA16219.pdf, Presented at a workshop on CO_2 geological storage in Canberra, Australia (19 January 2010)
Zhou C (2011) South East University, China, *personal communication* (May 2011)

12 Annex

Presentation of data on Chinese coal to chemicals gasification units

A1 Introduction

This annex presents the information collected on the various coal gasification technologies in use in China for non-power applications. It comprises a series of tables, one for each technology, which include information for those projects where the gasifiers are either operational or at the contracted design/construction stage. Thus Tables A1 to A8 provide key data on a licensor basis, where it has been found to be publically available, including:

- owner, application and location;
- type of feedstock and throughput;
- syngas production rate;
- type and mass of end products;
- mass of CO_2 produced;
- status (ie operational or at design construction stage).

For completeness, information for GE and Shell units that use either refinery residues or natural gas as feedstocks is also provided. All the other technology suppliers are only offering coal based systems within China.

With regard to existing or planned coal gasification projects for the reuse of the CO_2 extracted, the only CO_2 capture and storage project that is operational is a 100,000 t/y pilot trial at the Shenhua CTL demonstration plant, where the CO2 is transported and injected into an aquifer (*see* Chapter 8). At present, there are no firm plans for any additional projects on coal gasifiers either for aquifer storage or for use in EOR.

The approach adopted, to obtain the technical data for the tables, comprised:

- a review of the databases issued in 2010 by NETL and the Gasification Technologies Council to obtain a first listing of units and the relevant technical data. This provided a reasonable starting point while recognising that such databases only covered the international technology suppliers plus one domestic supplier, namely ECUST. In all cases, the information was not complete and there were some contradictions in the data available, which required clarification;
- a review of public dissemination announcements by the technology suppliers covering new licences to double check the databases and to seek additional information that is required for the study;
- a review of public dissemination announcements by the end users and by the suppliers of ammonia and methanol production equipment to gain information not made available by the licensors;
- a review of Chinese issued reports covering the development of coal to chemicals projects in order to gain additional information;
- face to face discussions with a wide range of companies in China to gather information, particularly for the domestic technology suppliers.

Specific data references for each technology are included with the respective table. It is important to recognise that the situation in China is complex, with the amount of information available for each project varying. In some cases, it has proved necessary to estimate some of the data, for example syngas quantities and end product quantities, where definitive data have not been reported, by correlating with known similar projects from the same licensor.

Based on the information gathered, estimates were made of the annual quantity of concentrated CO_2 that could be emitted from each process site, assuming maximum operational capacity for that period. These values represent the amount of CO_2 potentially available either for EOR, other utilisation prospects or storage. The approach adopted is in line with that used in a pilot study jointly funded by China and the USA (Zheng and others, 2010). In that earlier exercise, various emissions factors (EFs) for CO_2 release from various coal gasification processes were determined, based on the mass balance of the energy systems since the amount of CO_2 released varies with the shift reaction schemes to produce the various end products.

Five types of coal gasification based energy systems were considered, namely coal to urea plants (with ammonia first being produced as an intermediate and then used to manufacture the designated end product), coal to ammonia plants (ie the ammonia was not used for urea production but for other chemical processes), coal to methanol plants, coal to Fischer Tropsch liquids plants, and direct coal liquefaction plants (which incorporate coal gasification units for hydrogen production).

In summary, where the annual quantity of final product was either known or could be assumed based on data for a comparable process application, this number was multiplied by the relevant EF to give an estimate of the annual quantity of CO_2 emitted. Thus:

- for coal-to-ammonia plants an EF of 3.27 tCO_2/tNH_3 was assumed, this being an average of the factors applicable to the more established wet and dry coal feed systems;
- for coal to urea plants the factor was assumed to be 1.99 tCO_2/tNH_3, which is based on the assumption that, on a stoichiometric basis, ammonia would be used to synthesise urea at a rate of 1.76 $turea/tNH_3$ and that 0.73 tCO_2 (originally released in the ammonia process) would be needed to produce 1 tonne of urea. At some plants, it is understood that not all the ammonia is processed to produce urea. In those cases, the quantity of CO_2 emitted was calculated on a pro-rata basis;
- for coal-to methanol plants the factor was assumed to be 1.55 tCO_2/t methanol;
- for coal-to-synfuels via Fischer–Tropsch liquids (FTL) the factor used was 4.74 tCO_2/t FTL;
- for direct coal liquefaction it was 2.88 tCO_2 per tonne of liquids produced.

Supporting information for this approach is given in various publications (Meng and others, 2007; Wuhan Science and Technology, 2008; Larson and Ren, 2003; Kreutz and others, 2003; Zheng, 2010). That said, it is stressed that the information on possible CO_2 release from these coal transformation plants is indicative. It does not take into account the practical losses in the processes which vary with age and design of plant, scale and mode of operation.

The Chinese coal to chemicals sector is fast moving, with a considerable number of projects being proposed and declared publically to be proceeding. However, while the sector is growing rapidly, many of the proposed projects do not proceed for a wide range of reasons. Consequently, this survey has been limited to projects that are formally contracted to limit any misperceptions about gasifier application and implementation. Even so, while every effort has been taken to verify the information in the tables, there may be errors and omissions. Consequently, any interpretation of the data should be made with caution.

A2 References

Kreutz T, Larson E, Williams R, Liu G (2008) *Fischer-Tropsch fuels from coal and biomass*. Proceedings of 25th Annual International Pittsburgh Coal Conference, Pittsburgh, PA, USA, 29 September to 2 October 2008

Larson E, Ren T (2003) *Synthetic fuel production byindirect coal liquefaction*. Energy Sustainable Dev, 2003, 7, 79–102

Meng K, Williams R, Celia M (2007) *Opportunities for low cost CO_2 storage demonstration projects in China*, Energy Policy, 2007, 35, 2368–2378

Wuhan Science and Technology (2008) *Feasibility study of Hegang coal gasification based one million tonne urea project*. Project 06018-FP08-01G, Wuhan Science and Technology Co Ltd, Wuhan, China (2008)

Zheng Z, Larson E, Li Z, Liu G, Williams R (2010) *Near-term mega-scale CO_2 capture and storage demonstration opportunities in China*. Energy & Environmental Science 2010, 3, 1153-1169

Table A1 Listing of GE gasifiers in China

Information was obtained from a wide range of sources including:

China Automation Group (2009) *CAG acquires key coal chemical projects of Guizhou Province*. Available from: http://hk.todayir.com/todayirattachment/cag/html/20090907.php (7 September 2009)

Control Engineering (2006) *GE gasification technology licensed for China chemical plant expansion*. Available from: http://www.ceasiamag.com/article-1789-gegasificationtechnologylicensedforchinachemicalplantexpansion-Asia.html (7 August 2006)

DZWWW.COM (2005) *Sinopec introduces GE gasification technology*. Available from: http://www.dzwww.com/english/news/200512/t20051231_1311263.htm (29 December 2005)

ENN (2009) *ENN's 600,000 ton-a-year methanol project goes on line*. Available from: http://www.enn.cn/en/news/pr_20090730_918612.html (30 July 2009)

Gasification Technologies Council (2010) *Gasification Technologies Council Database 2010*. Available from: http://gasification.org (2010)

GE Energy (2006) *GE gasification technology licensed for chemical plant expansion in China*. Available from: http://192.131.225.60/about/press/en/2006_press/050906.htm (9 May 2006)

GE Energy (2007a) *Chemical facility in Inner Mongolia, China to use GE gasification technology*. Available from: http://www.gepower.com/about/press/en/2007_press/030107b.htm (1 March 2007)

GE Energy (2007b) *GE Energy signs its 30th gasification technology licensing agreement in China*. Available from: http://www.gepower.com/about/press/en/2007_press/030507.htm (5 March 2007)

GE Energy (2008a) *GE signs its 32nd gasification technology licensing agreement in China*. Available from: http://www.gepower.com/about/press/en/2008_press/021908.htm (19 February 2008)

GE Energy (2008b) *Latest licensing agreement further expands use of GE gasification technology in China's coal-to-chemicals industry*. Available from: http://www.gepower.com/about/press/en/2008_press/042208a.htm (22 April 2008)

GE Energy (2009) *GE Energy licenses its gasification technology to coal-to-methanol plant in China*. Available from: http://www.ge.com/cn/news/GE_ChinaMagazine_vol_60.pdf (15 July 2009)

GE Energy (2011) *Licensed facilities and summary data since 1950, personal communication* (January 2011)

GE in China (2010) *GE signs five gasification licensing agreements*. Available from: http://www.ge.com.cn/enewsletter/geinchina56.htm (24 May 2010)

NETL (2010) *NETL Gasification Projects Database 2010*. Available from: http://www.netl.doe.gov/technologies/coalpower/gasification/database/database.html (November 2010)

Press Release Point (2009) *GE Energy gasification technology selected by Hangzhou Jinjiang Group to help drive growth in chemicals production*. Available from: http://www.pressreleasepoint.com/ge-energy-gasification-technology-selected-hangzhou-jinjiang-group-tohelp-drive-growth-chemicals-pro (31 October 2009)

Thomas Net (2006) *GE gasification technology licensed for chemical plant expansion in China*. Available from: http://news.thomasnet.com/companystory/GE-Gasification-Technology-Licensed-For-Chemical-Plant-Expansion-In-China-484927 (9 May 2006)

Thomasnet (2007) *Chemical facility in Inner Mongolia, China to use GE gasification technology*. Available from: http://news.thomasnet.com/companystory/Chemical-Facility-in-Inner-Mongolia-China-to-Use-GE-Gasification-Technology-513885 (1 March 2007)

Wison (2009a) *Wison Nanjing signed gasification license agreement with GE Energy*. Available from: http://www.wison.com/en/news_details.php?cid=115&id=510&rn=71 (26 February 2009)

Wison (2009b) *Wison coal chemical phase II syngas project saw success in first feeding and start-up*. Available from: http://www.wison.com/en/news_details.php?cid=115&id=1075&rn=44 (9 September 2009)

World Fuels (2009) *GE wins gasification deal for Hangzhou Jinjiang*. Available from: http://www.worldfuels.com/wfExtract/exports/Content/ba2e4f12-b1a1-4ab5-ad74-82e623b46c6c.html (October 2009)

Various other indirect announcements attributed to GE and various end users as found on internet

Feedstock		Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
Type	Rate, t/d		Type	Annual rate, 10^3 t				
Vacuum Residue	900	2100/287	Ammonia	300	981	1983	Zhenhai Refining and Chemical Co Zhenhai Ammonia Plant	Ningbo Zhejiang Province
Vacuum Residue	740	2100/287	(Ammonia) Urea	(300) 520	(981) 597	1985	Sinopec Urumqi Ammonia Plant	Urumqi Xinjiang Uygur Auton Region
Vacuum Residue	75	210/29	Oxo-chemicals			1986	Sinopec Daqing Oxo-chemicals Plant	Daqing Heilongjiang Province
Vacuum Residue/ solids	1000	2500/342	Ammonia	360	11772	1988	CNOC Ningxia Daguan Refining and Chemical Co Ningxia Syngas Plant	Yinchuan Ningxia Autonomous Region
Heavy Fuel Oil	110	320/44	Oxo-chemicals			1995	Beijing No 4 Chemical Co Beijing Oxo-chemicals Plant	Beijing
Vacuum Residue	670	2097/287	Ammonia	300	981	1996	Dalian Chemical Industrial Co Dalian Ammonia Plant	Dalian Liaoning Province
Vacuum Residue/Pitch	385/ 385	2200/331	Ammonia	(300) 520	(981) 597	2002	Nanjing Chemical Industry Co Nanjing Ammonia Plant	Nanjing Jiangsu Province
Vacuum Residue	740	2097/287	Ammonia	300	981	2003	Jilin Chemical Industrial Co Jilin Ammonia Plant	Jilin City Jilin Province
Heavy fuel oil			Oxo-chemicals			2012*	PetroChina Daqing Petrochemical Co	Daqing Heilongjiang Province
Natural Gas			Ammonia			2000		
Natural Gas			Ammonia/ Urea			2003		
Coal	350	525/72	(Ammonia) Urea	(80) 140	(262) 159	1993	Lu Nan Chemical Industry Co Lu Nan Ammonia Plant	Lu Nan, Tengxian Shandong Province

Feedstock		Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
Type	Rate, t/d		Type	Annual rate, 10^3 t				
Coal	1500	1530/209	Methanol TownGas	200	310	1995	Shanghai Coking & Chemical Co Shanghai Coking and Chemical Plant	Wujing Shanghai
Coal	1640	2040/279	(Ammonia) Urea	(300) 520	(981) 597	1996	Weihe Chemical Fertiliser Co Shaanxi Ammonia plant	Xian Shaanxi Province
Coal		765/105	Methanol Town Gas Chemicals	100 – 200	155 – –	1997	Shanghai Coking & Chemical Co (Shanghai Pacific) Gas Plant No 2	Wujing Shanghai
Coal	900	1400/191	(Ammonia) Urea Methanol Chemicals	(180) 270 50	(589) 358 78 –	2000	Huainan General Chemical Works Hefei City Ammonia Plant	Hefei City Anhui Province
Coal	1000	2200/300	Ammonia/ Urea	(300) 525	(981) 597	2004	Heilongjiang Haolianghe Fertiliser Co Haolianghe Ammonia Plant	Haolianghe Heilongjiang Province
Coal/Petcoke	2200	2100/287	(Ammonia) Urea	(300) 525	(981) 597	2005	Sinopec Jinling Chemical Industry Co	Nanjing Jinling Jiangsu Province
Coal	1000	1925/263	Methanol	200	310	2005	Shanxi Shenmu Chemical Industrial Co Shaanxi Shenmu Chemical Plant Phase 1	Shenmu Shaanxi Province
Coal		2045/280	Methanol	300	465	2005	China 1 Expansion, GE Haolianghe Plant	Haolianghe Heilongjiang Province
Coal	1500	1275/174	Methanol	190	295	2005	China 2 GE Jinling Plant	Jinling, Nanjing Jiangsu Province
Coal		2100/287	Ammonia H_2	300	981 –	2005	China 3 GE China 3	
Coal		2100/287	(Ammonia) Urea	(300) 525	(981) 597	2005	China 4 GE China 4	

Feedstock		Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
Type	Rate ,tpd		Type	Annual rate, 10^3 t				
Coal/ Petcoke	1500	2100/	(Ammonia) Urea	(300) 525	(981) 597	2006	Sinopec, Nanjing Chemical Industry Group Nanjing Ammonia Plant	Nanjing Jiangsu Province
Coal		2900/395	Chemicals		–	2006	Weihe Chemical Co Wheihe Chemical Plant	Weinan Shaanxi Province
Coal		2080/284	Methanol	300	465	2006	GE China 5	Yulin Shaanxi Province
Coal		2500/	Methanol	400	620	2007	Shaanxi Shenmu Chemical Industrial Co Shaanxi Shenmu Chemical Plant Phase 2	Shenmu Shaanxi Province
Coal	1500	2050/	Methanol CO	200 300	310 –	2007	Wison Phase 1 Wison Chemicals and Town Gas Plant	Nanjing Chemical Industrial Park Jiangsu Province
Coal/ Petcoke		2400/	Oxo-chemicals		–	2008	Sinopec Qilu Sinpopec Qilu Chemicals Plant	Zibu City Shandong Province
Coal		2100/232	Ammonia	320	1046	2008	Dahua Group Dalian Ammonia Plant	Dalian Liaoning Province
Coal		1500/	Methanol	220	341	2008	Shanghai Coking & Chemical Co	Weiwei Shanghai
Coal		2050/	CO H_2 Syngas	300 21,000 m^3/h 11,000 m^3/h	– – –	2009	Wison Phase 2 Wison Chemicals and Town Gas Plant	Nanjing Chemical Industrial Park Jiangsu Province
Coal	10000	12000/	Methanol	1800	2790	2010	Shenhua Baotou Coal Chemicals Co Shenhua Baotou Methanol Plant	Baotou Inner Mongolia Auton. Region
Coal		4500/	Methanol	600	930	2010	ENN Xinneng Energy Corporation	Erdos Inner Mongolia

Feedstock		Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
Type	Rate, t/d		Type	Annual rate, 10^3 t				
Coal	5600	4300/	(Ammonia) Urea Methanol	(300) 520 300	(981) 597 465	2010	Guizhou Jinchi Chemical Co Tongzi Coal Chemical Plant	Hetaoping, Tongzi County Guizhou Province
Coal	500	890/	Oxo-chemicals	250	–	2010	Shandong Lihuayi Duowei Chemical Co Ltd	Dongying City Shandong Province
Coal		2100/	Ammonia	400	1308	2011*	Hangzhou Jinjiang Group Co Ltd Kuitun Jinjiang Chemical Co	Huangzhou Zhejiang Province
Coal			Methanol	1800	2790	2013*	Pucheng Clean Energy Chemical Co	Pucheng Henan Province
Coal		4520/	Methanol	600	930	2013*	Inner Mongolia Zhuozheng Coal Chemical Industry Co Ltd	Wushen Banner Inner Mongolia
Coal		2840/	Ammonia	400	1310	2013*	Shihlien Chemical Industrial Jiangsu Co	Huai'an Jiangsu Province
Coal			Methanol	600	930	2013*	Xuzhou Coal Mining Group Corporation	Baoji Shaanxi Province
Coal			Methanol	500	775	2013*	Guodian Younglight Energy Chemical Company	Yinchuan Ningxia Auton. Region
Coal		2100/	(Ammonia) Urea	(300) 525	(981) 597	2013*	CNOOC	Not known

* Engineering, design and construction phase with nominal expected start-up date included
Gasifier pressure for each unit is in the range 3.0–6.5 MPa
Products in brackets (typically ammonia) represent primary product from the gasifier prior to any subsequent processing (typically to urea). Net CO_2 release is determined on the basis of the urea production rate

Table A2 Listing of Shell gasifiers in China

Information was obtained from a wide range of sources including:

Chhoa T (2005) *Shell gasification business in action*. Available from: http://www-static.shell.com/static/globalsolutions/downloads/innovation/shell_gasification_business_in_action_v2.pdf, GTC (October 2005)

China Automation Group (2009) *CAG acquires key coal chemical projects of Guizhou Province*. Available from: http://www.cag.com.hk/html/20090907.php (7 September 2009)

China Knowledge (2007) *Shell wins 16th coal gasification contract in China*. Available from: http://www.chinaknowledge.com/Newswires/News_Detail.aspx?type=1&NewsID=12145 (14 December 2007)

NETL (2010) *Gasification projects database 2010*. Available from: http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html (9 November 2010)

Shell (2008) *Shell announces three new clean coal technology licenses in China*. Available from: http://www.shell.com.cn/home/content/chn-en/aboutshell/media_centre/news_and_media_releases/archive/2008/coaltech_20081120.html (20 November 2008)

Uhde (1997) *The Shell Gasification Process*. Available from: http://www.uhde.eu/cgi-bin/byteserver.pl/pdf/broschueren/Oil_Gas_Refinery/Shell_Gasification_Process.pdf (1997)

Zuideveld P, De Graaf J (2003) *Overview of Shell Global Solutions worldwide gasification development*. Proceedings Gasification Technologies 2003. Heil in San Francisco, California, USA, (12-15 October 2003)

Various Shell press releases and other announcements indirectly attributed to Shell as found on internet

Feedstock		Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
Type	Rate, tpd		Type	Annual rate, 10^3 t				
Vacuum residue	246	715/98	Methanol	110	170	1987	Qilu Petrochemical Industry Zibu Methanol and Oxochemicals Plant	Zibu Shandong Province
Vacuum residue	21	60/8	Oxochemicals		–	1991	Fushun Detergent Co Fushun Oxochemicals Plant	Fushan Liaoning Province
Vacuum residue	672	2100/287	Ammonia	310	1014	1996	Inner Mongolia Fertiliser Co Hohhot Ammonia Plant	Hohot Inner Mongolia
Vacuum residue	672	2100/287	Ammonia	310	1014	1996	Juijiang Petrochemical Co Juijiang Ammonia Plant	Jiujiang City Jiangxi Province
Petroleum		6350/868	Ethylene		–	2009	Fujian Refinery Ethylene Project	Quanzhou Fujian Province
Natural Gas	700	2100/287	Ammonia	310	1014	1998	Lanzhou Chemical Co Lanzhou Ammonia Plant	Lanzhou Gansu Province
Coal	2000	3410/466	(Ammonia) Urea	(500) 870	(1635) 1000	2006	Sinopec/Shell Coal Gasifier Co Dong Ting Ammonia Plant	Yueyang Hunan Province
Coal	2000	3500/466	(Ammonia) Urea	(500) 870	(1634) 1000	2006	Sinopec Hubei Fertiliser Co Hubei Ammonia Plant	Zhijiang City Hubei Province
Coal	900	1320/197	Ammonia	200	654	2006	Shuanghuan Chemical Co Yincheng Chemical Plant	Yingcheng Hubei Province
Coal	1100	1720/256	(Ammonia) Urea Methanol Chemicals	(300) 520 100	(981) 597 310 –	2006	Liuzhou Chemical Industry Co Liuzhou Ammonia Plant	Liuzhou Guangxi Auton. Region
Coal	2000	3410/500	(Ammonia) Urea	(500) 870	(1635) 1000	2006	Sinopec Anqing Co Anqing Ammonia Plant	Anqing Annhui Province

Feedstock		Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
Type	Rate, tpd		Type	Annual rate, 10^3 t				
Coal	1100	1700/232	Methanol	260	403	2007	Dahua Chemicals Co Dalian Carbon Chemicals Plant	Dalian Liaoning Province
Coal	2700	3400/465	(Ammonia) Urea	(500) 870	(1635) 1000	2008	Yuntianhua Chemicals, Anning Plant	Anning Yunnan Province
Coal	2700	3400/465	(Ammonia) Urea	(500) 870	(1635) 1000	2008	Yunzhanhua Chemicals, Huashan Plant	Qujing/Huashan Yunnan Province
Coal	2100	3100/424	Methanol	500	775	2008	Henan Longyu Co Yongcheng Chemicals Plant	Yongcheng Henan Province
Coal	4400	7400/861	H_2 for direct coal liquefaction process	1100	3168	2008	Shenhua Coal Liquefaction Co Majiata DCL Plant	Majiata, Ordos Inner Mongolia
Coal	1100	1720/257	Methanol	300	465	2008	Henan Kaixiang Group Yima Kaixiang Chemical Plant	Yima Henen Province
Coal	2100	3410/463	Methanol	500	775	2008	Zhong Yuan Dahua Group Ltd Puyang Methanol Plant	Puyang Henan Province
Coal	4000	8250/1124	Ammonia Methanol	500 500	1635 775	2010	Tianjin Bohai Chemical Group, Tianjin Bohai Chemical Plant	Tianjin Municipality
Coal	2000	3410/465	Ammonia Methanol	300 200	981 310	2010	Guizhou Tianfu Chemicals Co Guizhou Chemical Plant	Fuquan City Guizhou Province
Coal	8400	12276/ 1667	Methanol	1800	2790	2011*	Datang Energy & Chemicals Datang Inner Mongolia MTP Plant	Xilinguole Inner Mongolia
Coal	2100	4000/546	Methanol	600	930	2012*	Hebi Coal & Electricity Co Ltd Hebi Methanol Plant	Hebi Henan Province

Feedstock		Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
Type	Rate, tpd		Type	Annual rate, 10^3 t				
Coal	2100	3120/209	Methanol	500	775	On hold*	Henan Longyu Chemicals Co Yongcheng Longyu Chemicals Phase II Plant	Yongcheng Henan Province
Coal	2400	4000/546	Methanol	600	930	2013*	Tongmei Guangfa Chemicals Datong Tongmei Guangfa Methanol Plant	Datong Shanxi Province
Coal	1100	1700/232	Methanol	260	403	2013*	Yuntianhua Chemicals Co Shuifu Plant	Shuifu County Yunnan Province

* Engineering, design and construction phase with nominal expected start-up date included
Gasifier pressure for each unit is 4 MPa
All sites comprise one gasifier except Shenhua CTL plant (2 units), Tianjin Bohai Chemical Plant (2 units) and Datang Inner Mongolia Methanol Plant (3 units)
Products in brackets (typically ammonia) represent primary product from the gasifier prior to any subsequent processing (typically to urea). Net CO_2 release is determined on the basis of the urea production rate.

Table A3 Listing of other international gasifiers in China

Information sources include:

Euroinvestor (2008) *Synthesis Energy Systems and YIMA Coal Industry Group Co. Ltd. hold groundbreaking ceremony for new coal gasification to chemicals plant*. Available from: http://www.euroinvestor.co.uk/news/story.aspx?id=10088918 (19 December 2008)

GTC (2010) *Gasification Technologies Council database 2010*. Available from: http://www.gasification.org/database1/search.aspx (2010)

GTI (2008) *U-GAS Hai Hua coal gasification plant in China*. Available from: http://www.gastechnology.org/webroot/app/xn/xd.aspx?it=enweb&xd=1ResearchCap/1_8GasificationandGasProcessing/SignifResults/UGAS_Coal_Gasification.xml (2008)

Hydrocarbons-technology.com (2009) *Shenhua coal to liquids plant, China*. Available from: http://www.hydrocarbons-technology.com/projects/shenhua/ (2009)

Ma L (2009 *Future energy technology perspectives: coal technology assessment*. Available from: http://www.nzec.info/en/assets/Reports/NZECWP2.2-Technology-Assessment-Coal-TechnologiesFinal-report.pdf.WP2 China-UK NZEC Project (2009)

Morehead H (2008) *Siemens global gasification update*. Available from: http://www.syngasrefiner.com/SNG/Pres/HarryMorehead.pdf. Presented at Designing & operating US substitute natural gas plants, Houston, USA (10 April 2008)

Morehead H (2009) *Siemens IGCC and gasification activities: North America & China*. Available from: http://www.gasification.org/uploads/downloads/Conferences/2009/27MOREHEAD.pdf. Gasification Technologies Council Conference, Colorado, USA (5-7 October 2009)

NETL (2010) *Gasification projects database 2010*. Available from: http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html (9 November 2010)

PennEnergy (2011) *Siemens to supply eight 500MW coal gasifiers to one of China's biggest power generators*. Available from: http://www.pennenergy.com/index/power/display/0556570998/articles/pennenergy/power/coal/2011/july/siemens-to_supply.html (27 July 2011)

Coal feedrate, tpd	No of gasifiers + spare	Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
			Type	Annual rate, 10^3 t				
Siemens								
10000	5	12960/ 1735	Methanol	1500	2325	2011	Shenhua Ningxia Coal Group Ningxia Coal to Polypropylene Plant	Yinchuan Ningxia Hui Autonomous Region
2000	1+1		Ammonia Urea	(300) 520	(981) 597	2011*	Shanxi Lanhua Coal Chemical Co Ltd Jincheng Coal to Ammonia Plant	Jincheng Shanxi Province
16000	8	16000/	Methane	–	–	2014*	CPI Xinjiang Energy Co CPI Yinan SNG Plant	Yili City Xinjiang Province
Lurgi								
1200	4†	2282/312	Ammonia Urea	(300) 520	(981) 597	2000	Puyang Chemical Fertiliser Co Puyang Ammonia Plant	Puyang Henan Province
	4†	2282/312	Ammonia	300	981	1987	China National Technology Import Co Shaanxi Ammonia Plant	Shaanxi Province
	3†	2282/312	Methanol	350	543	2000	Zhong Yuan Dahua Group Zhong Yuan Dahua Chemicals Plant	Puyang Henan Province
1000		2050/	Ammonia Urea	(300) 520	(981) 597	2013*	Guodian Chifeng Chemical Co Chifeng Ammonia Plant	Chifeng Inner Mongolia
		10980/	Methane	–	–	2013*	Xinjiang Qinghua Energy Co	Yining County, Xinjiang Uygur Autonomous Region
		32980/	Methane	–	–	2013*	Datang International Keqi Gas Co	Keqi Inner Mongolia
3640		9150/	Methanol Methane	1200 –	1860 –	2014*	Xinjiang Guanghui Energy Co	Urumqi Xinjiang Province

Coal feedrate, tpd	No of gasifiers + spare	Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
			Type	Annual rate, 10^3 t				
		1560/	Ammonia Methanol	180 100	315 155	2014*	Shijiazhuang Jinshi Chemical Co	Shijiazhuang City Hebei Province
		38620/	Methanol LNG Petrol	500 147 156	775 – –	2014*	Yunnan Xianfeng Clean Energy Co	Xundian Yunnan Province
GTI U-Gas								
300	1	670/92	Methanol	100	155	2008	Synthesis Energy Systems-Shandong HaiHua Coal Co JV ZaoZhuang Methanol Plant	ZaoZhuang City Henan Province
2000		3750/512	Chemicals	–	–	2011*	Synthesis Energy Systems-Yima Coal Group JV Yima Chemicals Plant	Yima Henan Province

* Engineering, design and construction phase with nominal expected start-up date included
† Projects undertaken in conjunction with Sasol
Operating pressures for Siemens and Lurgi gasifiers are 4.0 MPa and 3.0–4.5 MPa respectively

Table A4 Listing of ECUST gasifiers in China

Information sources include:

Chemical Engineering (2010) *Coal to chemicals*. Available from: http://www.che.com/news/Coal-to-Chemicals_6368.html (1 February 2011)

Chemistry News (2011) *Coal-to-Chemicals*. Available from: http://chemnews.hoahocngaynay.com/article/259 (18 March 2011)

ECUST (2011) *Institute of Clean Coal Technology*. Available from: http://www.ecust.edu.cn/ (2011)

GTC (2010) *Gasification Technologies Council database 2010*. Available from: http://www.gasification.org/database1/search.aspx (2010)

Huang Z, Zhang J, Guangxi Yue G (2010) *Status of domestic gasification technology in China*. Available from: http://www.springerlink.com/content/7838522554310784/ Frontiers of Energy and Power Engineering in China, Volume 3, Number 3, 330-336, DOI: 10.1007/s11708-009-0021-1 (2010)

NETL (2010) *Gasification projects database 2010*. Available from: http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html (9 November 2010)

Wang F (2009) *Coal gasification technology in China*: Application and development. Available from: http://www.chinainvestsinamerica.com/files/China-US%20Clean%20Energy%20Seminar/Coal%20Gasification%20Technology%20in%20China(en).pdf. East China University of Science and Technology (2009)

Yu Z, Gong X, Wang F (2005) *Coal gasification technology in China*: Application and Development. Available from: http://gcep.stanford.edu/pdfs/wR5MezrJ2SJ6NfFl5sb5Jg/9_china_wangfuchen.pdf. East China University of Science and Technology (January 2005)

Zhou Z (2009) *Start-up of the 2000 tpd OMB gasifier at the Jiangsu Linggu Chemical & other activities updates*. Available from: http://www.gasification.org/uploads/downloads/Conferences/2009/18zhou.pdf . Presented at Gasification Technology Conference, Colorado Springs, USA (5 October 2009)

Various other announcements indirectly attributed to ECUST as found on internet

Coal feedrate, tpd	No of gasifiers + spare	Gasifer pressure, MPa	Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
				Type	Annual rate, 10^3 t				
750	1	6.5	1152/157	Methanol	100	155	2005	Hualu Hengsheng Group Hualu Hengsheng Chemicals Co	Dezhou Shandong Province
2300	2+1	4.0	3792/518	Methanol Power	240	372 –	2005	Yankuang Group Yankuang Cathay Coal Chemicals Co	Tengzhou City Shandong Province
1150	1	4.0	1896/259	Ammonia Methanol	240	372	2008	Yankuang Group Yankuang Lunan Fertiliser Plant	Tengzhou City Shandong Province
3000	2+1	6.5	4560/623	Methanol	500	755	2009	New Energy Phoenix (Tengzhou) Co Tengzhou Fenghuang Fertiliser Plant	Tengzhou City Shandong Province
1800	1+1	4.0	2832/387	Ammonia Urea	(400) 700	(1308) 796	2009	Jiangsu Linggu Chemicals Co Jiangsu Linggu Ammonia Plant	Yixing City Jiangsu Province
3000	2+1	6.5	5184/708	Methanol CO	600	930 –	2009	Jiangsu Sopo Group Jiangsu Sopo Plant	Zhejiang City Jiangsu Province
4000	2+1	4.0	5280/721	Methanol	750	1163	2010	Shenhua Ningxia Coal Group Shenhua Ningxia Yinchuan Methanol Plant	Yinchuan City Ningxia Province
2400	2+1	6.5	3600/492	Methanol Ammonia $CO + H_2$	240 80 40,000 m^3/h	372 262 –	2010	Ningbo Wanhua Co Ningbo Wanhua Polyeurethane Co	Ningbo City Zhejiang Province
2000	1	3.5	2760/377	Power	–	–	On hold*	China Huadian Power Group Hangzhou Banshan Power Plant	Huangzhou City Zhejiang Province
12000	6	6.5	14016/ 1914	Methanol	1990	3085	2013* On hold	Shandong Jiutai Co Shandong Jiutai Chemical Industry Plant	Linyi Shangdong Province
3000	2+1	6.5	4992/682	Methanol CO Acetic acid	600 250 500	930 – –	2012*	Shanghai Huayi Group Anhui Huayi Chemicals Plant.	Wuwei Anhui Province

Coal feedrate, tpd	No of gasifiers + spare	Gasifer pressure, MPa	Syngas output per day, 10^3 m^3 /MWth	Primary end p		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
				Type	Annual rate, 10^3 t				
4000	2	6.5	6288/859	Methanol	900	1395	2012*	Shandong Shengda Tech Co Shengda Ningdong Chemicals Co	Ningdong Ningxia Province
3000	2+1	6.5	7056/963	Ammonia Methanol	300 200	981 310	2012*	Yankuang Group Yankuang Xinjiang Coal Chemicals Co	Urumqi Xinjiang Province
2000	2+1	6.5	3280/448	Syngas	–	–	2012*	Shanghai Huayi Group Shanghai Coking & Chemical Corporation	Shanghai Municipality
2400			3360/459	Ammonia	455	1488	2012*	Yankuang Group Guizhou Kaiyang Chemical Co†	Kaiyang County Guizhou Province
5000	2+1	6.5	6720/918	Methanol	900	1395	2012*	Yankuang (Inner Mongolia) Rongxin Group Inner Mongolia Rongxin Chemicals Plant	Rongxin Inner Mongolia
3000	2+1	6.5	4080/557	Methanol	600	930	2013*	China Oceanwide Energy Group China Oceanwide Baotou Coal Chemicals Plant	Baotou Inner Mongolia
2000	1+1	4.0	2832/387	Ammonia Syngas		– –	2013*	Shandong Haili Industrial Group Shandong Haili Chemicals Plant	Maqiao Town, Huantai County, Zibo, Shandong Province
2200		4.0	2950/404	Ammonia	400	620	2013*	Yingde Gases Yingde Gases in Anyang	Anyang Henan Province

* Engineering, design and construction phase with nominal expected start-up date included
† Site may also include two Choren gasifers under construction but no details are available in the public domain
Products in brackets (typically ammonia) represent primary product from the gasifier prior to any subsequent processing (typically to urea). Net CO_2 release is determined on the basis of the urea production rate

Table A5 Listing of TPRI gasifiers in China

Information sources include:

EmberClear (2011) *Gasification*. Available from: http://www.emberclear.com/Gasification.html (2011)

Huang Z, Zhang J, Guangxi Yue G (2010) *Status of domestic gasification technology in China*. Available from: http://www.springerlink.com/content/7838522554310784/ Frontiers of Energy and Power Engineering in China, Volume 3, Number 3, 330-336, DOI: 10.1007/s11708-009-0021-1 (2010)

Ma L (2009 *Future energy technology perspectives: coal technology assessment*. Available from: http://www.nzec.info/en/assets/Reports/NZECWP2.2-Technology-Assessment-Coal-TechnologiesFinal-report.pdf. WP2 China-UK NZEC Project (2009)

Thermal Power Research Institute (2009) *GreenGen-near zero emission coal based power demonstration project in China*. Available from: http://www.gasification.org/uploads/downloads/Conferences/2009/13SHISEN.pdf. Gasification Technologies Council Conference, Colorado, USA (5-7 October 2009)

Zhang J (2011) Tsinghua University, Beijing, China, *personal communication* (May 2011)

Coal feedrate, tpd	No of gasifiers + spare	Syngas output per day, 10^3 m^3 /MWth)	Primary end products		Start-up	Net annual CO_2 stream, 10^3 t	Licensee/owner and plant name	Location
			Type	Annual rate, 10^3 t				
1000	1	1970/	Methanol	300	465	2011*	Wushenqi Shilin Chemical Industry Shilin Methanol Plant	Shilin Inner Mongolia
2800	2	4080/	Methanol	600	930	2012*	Hulanbeir Dongneng Chemical Co	Hulanbei Inner Mongolia
2000	1	3290/	Power		–	2011*	GreenGen IGCC	Tianjin Municipality

* Engineering, design and construction phase with nominal expected start-up date included
Does not include small industrial pilot operation in Shaanxi Province
Gasifers operate at either 3.0 or 4.0 MPa

Table A6 Listing of HT-L gasifiers in China

Information sources include:

China Aerospace Consulting Corporation (2011) *HT-L coal gasification technology*. Available from: http://www.castcc.com/en/show.php?id=50 (2011)

Huang Z, Zhang J, Guangxi Yue G (2010) *Status of domestic gasification technology in China*. Available from: http://www.springerlink.com/content/7838522554310784/. Frontiers of Energy and Power Engineering in China, Volume 3, Number 3, 330-336, DOI: 10.1007/s11708-009-0021-1 (2010)

Ma L (2009 *Future energy technology perspectives: coal technology assessment*. Available from: http://www.nzec.info/en/assets/Reports/NZECWP2.2-Technology-Assessment-Coal-TechnologiesFinal-report.pdf. WP2 China-UK NZEC Project (2009)

Zhang J (2011) Tsinghua University, Beijing, China, *personal communication* (May 2011)

Coal feedrate, tpd	No of gasifiers + spare	Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
			Type	Annual rate, 10^3 t				
500	1	1080/	Methanol	150	233	2008	Puyang Longyu Chemical Co Puyang Longyu Methanol Plant	Puyang Henan Province
570	1	1175/	Methanol	150	233	2008	Anhui Linquan Chemical Industrial Co Anhui Linquan Methanol Plant	Fuyang Anhui Province
1000	2	2300/	Methanol	300	465	2011*	Henan Xinxiang Zhongxin Chemical Co Henan Xinxiang Zhongxin Chemical Fertiliser Plant	Xinxiang Henan Province
1000	1+1	2325/	(Ammonia) Urea	(300) 520	(981) 597	2011*	Luxi Chemical Group Luxi Ammonia Plant	Luxi Shandong Province
1000	1+1	2210/	Ammonia	300	981	2011*	Shandong Rising Chemical Co Shandong Rising Chemical Ammonia Plant	Wuyue Shandong Province
860	1+1	2400/	Methane	–	–	On hold	Cheng-Feng Petrochemical Co Cheng-Feng Methane Co	Erdos Inner Mongolia
2000	2	4080/	Ammonia	600	1962	2012*	Henan Jinkai Investment Holding Group Henan Jinkai Ammonia Plant	Kaifeng Henan Province
2000	2	4080/	Ammonia	600	1962	2012*	Henan Jinkai Investment Holding Group Phase 2 Henan Jinkai Ammonia Plant Phase 2	Kaifeng Henan Province
1000	2	2160/	Methanol	300	465	2013*	Heilongjiang Longmei Mining Group Longmei Ammonia Plant	Shuangyashan Heilongjiang Province
600	1	1230/	(Ammonia) Urea	(180) 312	(590) 359	2012*	Anhui Linquan Chemical Industrial Co Anhui Linquan Ammonia Plant	Linquan Anhui Province
1000	2	2160/	(Ammonia) Urea	(300) 520	(981) 597	2013*	Anhui Haoyuan Chemical Industry Co Anhui Haoyuan Ammonia Plant	Fuyang Anhui Province
2000	2	4080/	Ammonia Urea	(570) 988	(1864) 1134	2013*	Haohua-Junhua Group Haohua Junhua Ammonia Plant	Zhengyang Henan Province

Coal feedrate, tpd	No of gasifiers + spare	Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
			Type	Annual rate, 10^3 t				
1500	2+1	3360/	Ammonia Urea	(467) 809	(1527) 930	2013*	Sichuan Chemical Industry Co Sichuan Chemical Industry Ammonia Plant	Sichuan Province
1000	2	2160	Ammonia Urea	(300) 520	(981) 597	2013*	Luneng Baoqing Coal Electricity Chemistry Development Co Luneng Baoqing Ammonia Plant	Baoqing Heilongjiang Province
600	1	1230/	Ammonia Urea	(170) 295	(556) 339	2013*	Xinjiang Zhongneng Wanyuan Chemical Co Xinjiang Zhongneng Wanyuan Ammonia Plant	Zhongneng Xinjiang Province
4000	4	8160/	Methanol	1800	2790	2013*	Ningxia Baofeng Energy Group Co	Yinchuan City Ningxia Hui Auton Region
2000	2	4080/	Ammonia Urea	(570) 988	(1864) 1134	2014*	Henan Yangmei Zhengyuan Chemical Group Co	Henan Province
2000	2	5040/	Ammonia Urea	(704) 1220	(2302) 1400	2014*	Inner Mongolia Elion Group Corporation	Inner Mongolia

* Engineering, design and construction phase with nominal expected start-up date included
All gasifers operate at 4.0 MPa
Products in brackets (typically ammonia) represent primary product from the gasifier prior to any subsequent processing (typically to urea). Net CO2 release is determined on the basis of the urea production rate

Table A7 Listing of Tsinghua University gasifiers in China

Information sources include:

Huang Z, Zhang J, Guangxi Yue G (2010) *Status of domestic gasification technology in China*. Available from: http://www.springerlink.com/content/7838522554310784/. Frontiers of Energy and Power Engineering in China, Volume 3, Number 3, 330-336, DOI: 10.1007/s11708-009-0021-1 (2010)

Ma L (2009 *Future Energy Technology Perspectives: Coal Technology Assessment*. Available from: http://www.nzec.info/en/assets/Reports/NZECWP2.2-Technology-Assessment-Coal-TechnologiesFinal-report.pdf. WP2 China-UK NZEC Project (2009)

Zhang J (2011) Tsinghua University, Beijing, China, *personal communication* (May 2011)

Various other announcements indirectly attributed to Tsinghua University as found on internet

Coal feedrate, tpd	No.of gasifiers + spare	Gasifer pressure, MPa	Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
				Type	Annual rate, 10^3 t				
500	1+1	4.0	660/	Methanol	100	155	2006	Yangmei Group Shanxi Yangmei Fengxi Fertiliser Industry Group	Yuncheng Shanxi Province
700	1	4.0	984/	Methanol	100	155	2009	Yangmei Group Shanxi Yangmei Fengxi Fertiliser Industry Group (Linyi)	Yuncheng Shanxi Province
1000	2+1	4.0	1056/	Acetic acid		–	On hold	Shanxi Coking Co Shanxi Coking Plant	Linfen Shanxi Province
1400	2+1	6.5	2400/	Methanol	300	465	2011*	Eerduosi Jinchengtai Chemical Co Eerduosi Jinchengtai Methanol Plant	Eerduosi Inner Mongolia
1800	1+1	6.5	2640	Methanol	400	620	2011*	Eerduosi Guotai Chemical Co Eerduosi Guotai Methanol Plant	Eerduosi Inner Mongolia
500	1+1	4.0	1300	Ammonia	180	590	2011*	Datang Hulunbuir Fertiliser Co Datang Hulunbuir Ammonia Plant	Hulunbuir Inner Mongolia
1000	1	4.0	2900	Ammonia	400	1310	2011*	Yangmei Group Shanxi Yangmei Fengxi Fertiliser Industry Group	Yuncheng Shanxi Province
500	1	3.5	7176	Cyclohexanone		–	2012*	Jiangsu Yongpeng Industrial Co Jiangsu Yongpeng Chemicals Plant	Jiangsu Province

* Engineering, design and construction phase with nominal expected start-up date included

Table A8 Listing of ICC-CAS gasifiers in China

Information sources include:

Huang Z, Zhang J, Guangxi Yue G (2010) *Status of domestic gasification technology in China*. Available from: http://www.springerlink.com/content/7838522554310784/. Frontiers of Energy and Power Engineering in China, Volume 3, Number 3, 330-336, DOI: 10.1007/s11708-009-0021-1 (2010)

Li W (2010) *R&D activities of coal to fuel/chemicals technology in China*. Available from: http://www.cleanenergy8.or.kr/result/PL/PL-4_Wen_Li.pdf. Presented at 8th Korea-China clean energy workshop, Daejeon, Republic of Korea (23-27 November 2010)

Ma L (2009) *Future energy technology perspectives: coal technology assessment*. Available from: http://www.nzec.info/en/assets/Reports/NZECWP2.2-Technology-Assessment-Coal-TechnologiesFinal-report.pdf. WP2 China-UK NZEC Project (2009)

Zhang J (2011) Tsinghua University, Beijing, China, *personal communication* (May 2011)

Zhang Y (2010) *Fluidised bed gasification for fuel gas*. Available from: http://www.gasification-freiberg.org/PortalData/1/Resources/documents/paper/06-4-zhang__yongqi.pdf. Institute of Coal Chemistry- Chinese Academy of Sciences. Presented at the Freiberg Gasification Conference, Germany (2010)

Coal feedrate, tpd	No of gasifiers + spare	Syngas output per day, 10^3 m^3 /MWth	Primary end products		Net annual CO_2 stream, 10^3 t	Start-up	Licensee/owner and plant name	Location
			Type	Annual rate, 10^3 t				
100	1	216/	Ammonia	20	65	2007	Shanxi Chenggu Fertiliser Corporation Chenggu Ammonia Plant	Chenggu Shanxi Province
300	1	648/	Ammonia	60	196	2009	Shijiazhuang Jinshi Chemical Fertiliser Co	Shijiazhuang Hebei Province
1800	6	3900/	Methanol	300	465	2010	Shanxi Jincheng Anthracite Mining Group Jincheng Methanol Plant	Jincheng Shanxi Province

Operating pressure is in the range 1.0–3.0 MPa